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Sea level reconstruction: Exploration of methods for combining altimetry with other data to beyond the 20-year altimetric record

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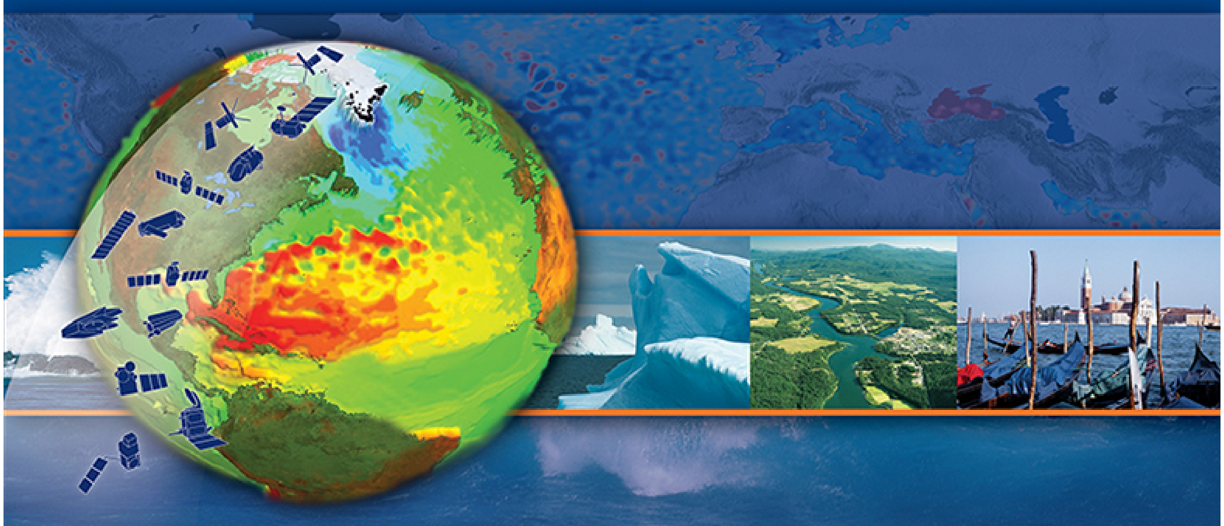
→ 20 YEARS OF PROGRESS IN RADAR ALTIMETRY SYMPOSIUM



24-29 September 2012 | Venice, Italy

ABSTRACT BOOK

20 Years of Progress in Radar Altimetry Symposium

24-29 September 2012, Venice, Italy

Abstract Book

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Opening Session & Keynote Presentations

The Challenges in Long-term Altimetry Calibration for Addressing the Problem of Global Sea Level Change

Fu, Lee-Lueng; Haines, Bruce
Jet Propulsion Laboratory, UNITED STATES

Long-term change of the global sea level resulting from climate change has become an issue of great societal interest. The advent of the technology of satellite altimetry has modernized the study of sea level on both global and regional scales. In combination with in-situ observations of the ocean density and space observations of Earth's gravity variations, satellite altimetry has become an essential component of a global observing system for monitoring and understanding sea level change. The challenge of making sea level measurements with sufficient accuracy to allow the patterns of natural variability to be distinguished from those linked to anthropogenic forcing rests largely on the long-term efforts of altimeter calibration and validation. The issues of long-term calibration for the various components of the altimeter measurement system are reviewed in the paper. The topics include radar altimetry, the effects of tropospheric water vapor, orbit determination, gravity field, tide gauges, and the terrestrial reference frame. The necessity for maintaining a complete calibration effort and the challenges of sustaining it into the future are discussed.

From Satellite Altimetry to Operational Oceanography: a Historical Perspective

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Ifremer/ Mercator Océan, FRANCE

The launch of the US/French mission Topex/Poseidon (T/P) (CNES/NASA) in August 1992 was the start of a revolution in oceanography. For the first time, a very precise altimeter system optimized for large scale sea level and ocean circulation observations was flying. Topex/Poseidon revolutionized our vision and understanding of the ocean. It provided new views of the large scale seasonal and interannual sea level and ocean circulation variations. T/P alone could not observe the mesoscale circulation. In the 1990s, the ESA satellites ERS-1/2 were flying simultaneously with T/P. The ERS-1/2 orbit was well adapted for mesoscale circulation sampling but the orbit determination and altimeter performance were less precise than for T/P. We demonstrated that we could use T/P as a reference mission for ERS-1/2 and bring the ERS-1/2 data to an accuracy level comparable to T/P. This was an essential first step for the merging of T/P and ERS-1/2. The second step required the development of a global optimal interpolation method. Near real time high resolution global sea level anomaly maps were then derived. These maps have been operationally produced as part of the SSALTO/DUACS system for the last 15 years. They are now widely used by the oceanographic community and have contributed to a much better understanding and recognition of the role and importance of mesoscale dynamics. The unique capability of satellite altimetry to observe the global ocean in near real time at high resolution was also essential to the development of global ocean forecasting. The Global Ocean Data Assimilation Experiment (GODAE) (1998-2008) was phased with the T/P and ERS-1/2 successors (Jason-1 and ENVISAT) and was instrumental in the development of global operational oceanography capabilities.

The presentation will provide an historical perspective on the development of SSALTO/DUACS altimeter products and on the development of GODAE and its links with the OSTST.

A 20 Year Climate Data Record of Sea Level Change: What Have We Learned?

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[1]University of Colorado, UNITED STATES; [2]University of South Florida, UNITED STATES; [3]University of Hawaii, UNITED STATES

Much has been made of the 20-year climate data record of sea level change that has been assembled from the satellite altimeter record. But what have we learned from this record? This presentation will summarize our current understanding of sea level change based on the satellite altimeter record, the satellite gravity record, and the tide gauge record and other in situ measurements. The rate of sea level rise was 50% higher during the first decade as compared to the second decade, which has been widely attributed to ENSO variability, but a broader interpretation of this result is lacking. One important fact we have learned from these observations is that the 20-year altimeter record occurs during a remarkably unusual time in the 100+ year sea level record. As a result, we must ask ourselves how this affects our interpretation of the altimeter record - are the changes we are observing short term or long term? Sorting out the natural and anthropogenic climate signals is a continuing challenge as we move into the future and look for answers to the many questions that remain. This is also an appropriate time to pause and ask if we have the measurements we need to answer these questions, or if new measurements are needed? Several new satellite measurement systems are planned - how will they enhance our understanding of sea level change? This presentation will look back at the 20-year satellite altimeter record - but also look forward to measurements and discoveries yet to be made.

Warming in the Southern Ocean: Assessing the Mechanisms with Altimetry and Argo

Gille, Sarah; Gilroy, Angelica; Mazloff, Matthew; Zajaczkovski, Uriel
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Comparisons of historical hydrographic data with modern measurements from profiling floats indicate that the Southern Ocean has warmed measurably since the 1950s. This warming could be a sign of increased poleward eddy heat transport or of a poleward displacement of the entire Antarctic Circumpolar Current (ACC), possibly in response to a decadal-scale intensification of the Southern Annular Mode (SAM). The long-term warming trend suggests the possibility that more (or warmer) Upper Circumpolar Deep Water may be coming into contact with the Antarctic Ice Shelves, particularly in regions where the southern edge of the ACC is closest to the Antarctic continent (i.e. in the Indian Ocean sector, between 40°E and 160°E, and in the eastern Pacific, between 140°W and 50°W, near Pine Island Glacier.) The twenty-year record from satellite altimetry is an important source of information for evaluating the mechanisms governing these trends. Satellite altimeter data indicate that short-term meandering of the ACC tracks the SAM on monthly to seasonal scales and is closely linked to El Niño variability on seasonal to interannual timescales. Meandering of the ACC at annual frequencies is difficult to evaluate because the signal is biased by annual variations in steric sea level. On decadal scales, the sea surface height signal is hypothesized to track the SAM, but it appears that a longer altimeter record will be required to evaluate this hypothesis. To assess the implications of the meandering ACC, we use the Southern Ocean State Estimate (an assimilating model that is constrained both by altimetry and Argo observations) to evaluate the relative contributions of air-sea fluxes, horizontal advection, and diffusion. Near Pine Island Bay all three processes contribute significantly to the time evolution of the heat budget.

The Ocean Mean Dynamic Topography: 20 Years of Improvements

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[1]CLS, FRANCE; [2]CNES, FRANCE

Since the very beginning of altimetry, 20 years ago, the lack of an accurate geoid has hampered the direct use of altimeter signal for computing the ocean absolute dynamic topography and, hence, by geostrophy, the ocean surface currents. To cope with the uncertainty on the geoid, the so-called 'repeat-track' method has been developed and Sea Level Anomalies (SLA) are computed with centimetre accuracy. To correctly analyse the altimeter signal and assimilate it into operational forecasting systems, the full dynamical signal needs to be reconstructed from the SLA. Knowledge of the ocean Mean Dynamic Topography (MDT) is therefore required with both high accuracy and high resolution. At large spatial scale, the MDT may be obtained by filtering the difference between an altimetric Mean Sea Surface and a geoid model. The filtering length is imposed by the geoid commission and omission error level. With the launch of dedicated space gravity missions as CHAMP (2000), GRACE (2004) and GOCE (2009) huge improvements have been made in the last 20 years for the estimation of the geoid. Recent satellite-only geoid models based on GRACE and GOCE data have centimetre accuracy at spatial scales down to around 150 km.

To compute higher resolution MDT, a number of methodologies have been developed. The geoid itself can be improved at short scales locally using in-situ gravimetric data or globally using the shortest scales information of the altimetric Mean Sea Surface. On the other hand, the large-scale MDT based on the satellite-only geoid models may be improved thanks to the use of in-situ oceanographic measurements (drifting buoy velocities, dynamic heights from hydrological profiles). Alternatively, the synthesis of all available information (in-situ oceanographic data, altimetry) can be done in a dynamically consistent way through inverse modeling or through data assimilation into ocean general circulation models, whose outputs are then averaged to obtain an estimate of the ocean Mean Dynamic Topography.

The aim of this talk is to give an overview of the huge improvements that have been achieved in the past 20 years for the estimation of the ocean Mean Dynamic Topography thanks to the launch of dedicated space gravimetry missions, the development of new computation methodologies, and the increasing number of oceanographic in-situ data. Perspectives will also be given in the upcoming context of high resolution wide-swath altimetry, and increasing need for high resolution coastal products.

Self-Induced Ekman Pumping Over Oceanic Mesoscale Eddies

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An eddy detection algorithm applied to 18 years of SSH fields identifies about 1600 mesoscale eddies with lifetimes of 8 weeks or longer in the California Current System (CCS). More than 95% of these have nonlinearity parameter U/c>1, where U is the maximum rotational speed of the eddy and c is its translation speed, and can thus transport trapped fluid. Most of the eddies form within 50iV100 km of the coast. The mean eddy amplitude and nonlinearity are maximum about 200-300 km from the coast.

Overall, there is a moderate preference for anticyclones, which outnumbered cyclones by about 850 to 750 over the 18-year period. About 125 eddies of each polarity propagated more than 500 km. For longer propagation distances, anticyclones outnumbered cyclones. An abrupt decrease of the mean amplitudes of cyclones beyond 500-600 km from the coast suggests a more rapid decay of cyclones, possibly because they have shallower vertical extent than anticyclones. Eddies of both polarities tend to be deflected slightly equatorward from due west, with overall average deflections of 3.3"a for cyclones and 16.3"a for anticyclones. About 30% of the cyclones and 5% of the anticyclones were deflected slightly poleward.

The performance of the automated eddy tracking procedure is assessed from comparisons with the trajectories of about 20 RAFOS floats launched at a depth of about 300 m. Beyond about 100 km from the coast, most of the floats become trapped in mesoscale eddies with a strong preference for trapping in anticyclones. The wandering of some of the floats from one eddy to another can almost always be explained by superposing the float trajectories on the SSH fields. Three of the floats remained trapped in single tracked anticyclones for about a year. A comparison of the looping trajectories in Lagrangian reference frames moving with the SSH centroids of each of these three tracked eddies and with the centroids of the float trajectories suggests a noise level of less than 50 km in the locations of the SSH centroids.

The strong preference for trapping of the floats in anticyclones is perhaps the most intriguing aspect of this analysis. We believe that this is because relatively few cyclones extend to the float depths of ~300 m. This speculation is supported anecdotally from past hydrographic surveys of the CCS, which have suggested that cyclones form by the pinching off of meanders of the shallow equatorward surface currents, while anticyclones form by the pinching off of meanders of the poleward undercurrent. This difference in the penetration depths of cyclones and anticyclones has been reproduced in a recent numerical simulation of the CCS and is further validated here from composite averages of the vertical structures of temperature, salinity and geostrophic velocity computed separately from Argo profiles collocated to the interiors of each eddy polarity.

Twenty Years of Progress on Global Ocean Tides: The Impact of Satellite Altimetry

Egbert, Gary[1]; Ray, Richard[2]
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At the dawn of the era of high-precision altimetry, before the launch of TOPEX/Poseidon, ocean tides were properly viewed as a source of noise--tidal variations in ocean height would represent a very substantial fraction of what the altimeter measures, and would have to be accurately predicted and subtracted if altimetry were to achieve its potential for ocean and climate studies. But to the extent that the altimetry could be severely contaminated by tides, it also represented an unprecedented global-scale tidal data set. These new data, together with research stimulated by the need for accurate tidal corrections, led to a renaissance in tidal studies in the oceanographic community. In this paper we review contributions of altimetry to tidal science over the past 20 years, emphasizing recent progress. Mapping of tides has now been extended from the early focus on major constituents in the open ocean to include minor constituents, (e.g., long-period tides; non-linear tides in shelf waters, and in the open ocean), and into shallow and coastal waters. Global and spatially local estimates of tidal energy balance have been refined, and the role of internal tide conversion in dissipating barotropic tidal energy is now well established through modeling, altimetry, and in situ observations. However, energy budgets for internal tides, and the role of tidal dissipation in vertical ocean mixing remain controversial topics. Altimetry may contribute to resolving some of these important questions through improved mapping of low-mode internal tides. This area has advanced significantly in recent years, with several global maps now available, and progress on constraining temporally incoherent components. For the future, new applications of altimetry (e.g., in the coastal ocean, where barotropic tidal models remain inadequate), and new mission concepts (studies of the submesoscale with SWOT, which will require correction for internal tides) may bring us full circle, again pushing further development of tidal models as corrections.

Conquering the coastal zone: a new frontier for satellite altimetry

Cipollini, Paolo[1]; Benveniste, Jérôme[2]; Miller, Laury[3]; Picot, Nicolas[4]; Scharroo, Remko[5]; Strub, P. Ted[6]; Vandemark, Doug[7]; Vignudelli, Stefano[8]; Andersen, Ole B.[9]; Birol, Florence[10]; Coelho, Emanuel[11]; Deng, Xiaoli[12]; Emery, William J.[13]; Fenoglio-Marc, Luciana[14]; Gómez-Enri, Jesus[15]; Griffin, David[16]; Fernandes, M. Joana[17]; Han, Guoqi[18]; Hausman, Jessica[19]; Ichikawa, Kaoru[20]; Kourafalou, Villy[21]; Labroue, Sylvie[22]; Ray, Richard[23]; Saraceno, Martín[24]; Smith, Walter H. F.[3]; Thibaut, Pierre[22]; Wilkin, John[25]
[1]National Oceanography Centre, UNITED KINGDOM; [2]ESA/ESRIN, ITALY; [3]NOAA, UNITED STATES; [4]CNES, FRANCE; [5]NOAA & Altimetrics LLC, UNITED STATES; [6]Oregon State University, UNITED STATES; [7]University of New Hampshire, UNITED STATES; [8]CNR, ITALY;[9]DTU Space, DENMARK; [10]LEGOS, FRANCE; [11]Stennis Space Center, UNITED STATES; [12]University of Newcastle, AUSTRALIA; [13]University of Colorado, UNITED STATES; [14]TU Darmstadt, GERMANY; [15]University of Cadiz, SPAIN; [16]CSIRO, AUSTRALIA; [17]University of Porto, PORTUGAL; [18]Fisheries and Oceans, CANADA; [19]JPL, UNITED STATES; [20]Kyushu University, JAPAN; [21]University of Miami, UNITED STATES; [22]CLS Toulouse, FRANCE; [23]NASA GSFC, UNITED STATES; [24]CONICET-UBA, ARGENTINA; [25]Rutgers University, UNITED STATES

Coastal altimetry, that is the effort to recover meaningful measurements of sea level and significant wave height in the coastal strip from satellite-borne radar instruments, is successfully extending altimetry to a previously uncharted domain. This success is apparent at the annual *Coastal*

Altimetry Workshops, whose 5th edition (San Diego, Oct 16-18, 2011) was attended by more that 130 delegates from 21 different countries.

The efforts of such a vibrant international community are bringing coastal altimetry to maturity, as a science topic of great relevance to monitor the coastal environment and assess the impact of global change on the coasts. Datasets are being produced, results are coming out and being disseminated, applications are pioneered. The Springer book *Coastal Altimetry*, published in 2011, is a good account of such efforts. The cross-fertilization of ideas with OSTST (of which the coastal altimetry community constitutes a special splinter) brings significant mutual benefits, both in terms of technical insight and in terms of synergy of open-ocean and coastal applications.

The present contribution is meant as a 'community white paper' and aims at giving a full account of the development and accomplishments of the new field. We will summarize the main technical achievements and the many diverse applications of the new discipline, which were showcased in more than 60 presentations and posters in San Diego, as well as the recommendations that stemmed from the discussion. While coastal altimetry techniques are recovering extremely valuable information from the 20+ years of data already in the archives, even more exciting prospects are ahead of us with the processing of higher resolution altimetric missions (CryoSat, Sentinel-3, Jason-CS, SWOT).

The community-led review will continue with the next edition (6th) of the Coastal Altimetry Workshop, being held on Sept 20-21, 2012, just before the "20 Year of Progress in Radar Altimetry" Symposium. The updated findings and recommendations from the 6th Workshop will be included in the present contribution.

Advances in our Understanding of the Polar Ice Sheets due to Satellite Altimetry

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After a century of polar exploration, the past two decades of satellite measurements have painted an altogether new picture of how Earth's ice sheets are changing. As global temperatures have risen, so too have rates of snowfall, ice melting, and glacier flow. While the balance between these opposing processes has varied considerably on a regional scale, satellite observations have revealed that Antarctica and Greenland are each losing mass overall. Our best estimate of their combined imbalance suggests that they currenlty provide only a modest contribution to the rate of global sea level rise. However, much of the losses result from the flow of glaciers into the ocean which have accelerated over the satellite era. In both continents, there are suspected triggers for the accelerated ice discharge - surface and ocean warming, respectively - and, over the 21st century, these processes could rapidly counteract the snowfall gains predicted by present coupled climate models. It is clear that satellite altimeter observations have proved central to our awareness and understanding of these changing events and, in the absence of accurate numerical predictions, they will remain our most important dataset for observing the impacts of climate change upon the cryosphere. This presentation will provide an overview of the contribution two decades of satellite altimetry has made to our understanding of the polar ice sheets.

20 Years of River and Lake Monitoring from Multi-mission Satellite Radar Altimetry

Berry, Philippa A.M.[1]; Smith, Richard G.[1]; Witheridge, Simon[1]; Salloway, Mark K.[1]; Benveniste, Jérôme[2]
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Measurement of surface inland water using satellite radar altimetry has a significant history, from the first tentative time series over the Amazon basin and Tonle Sapp (derived using a constrained quantity of Geosat waveform data), progressing to the current global observation capability. This paper presents an overview of this rapidly advancing field, discussing the current dataset availability, and analysing the current and future monitoring capability for inland water targets, using waveform data from TOPEX, Jason1, Jason2, ERS1, ERS2, EnviSat and CryoSat2. The paper also showcases the impact of these data on a range of scientific and operational applications. A key factor for inland water height retrieval from satellite radar altimetry is the ability to maintain lock over varying terrain. Here the ocean-optimised missions, TOPEX, Jason1 and Jason2 show a relatively poor retrieval capability of useable waveforms (primarily failure to capture the waveform leading edge). In contrast, the ESA altimeters are able to retrieve waveforms from inland water targets in far rougher terrain, with the EnviSat RA-2 successfully retrieving data from 25636 targets, of which 15067 are currently useable. The ability to 'retrack' inland water waveforms to obtain an accurate range to surface estimates is also essential for successful height retrieval over most of the world's inland water surfaces. Pre-selection of echoes that may be returned from inland water surfaces is helpful, and results are presented demonstrating that pre-selecting waveforms based on an accurate target mask can increase target retrieval by a factor of ten. The results presented here confirm that only a tiny fraction (less than 20%) of the inland water targets overflown over the past 20 years have returned waveforms which have been successfully interpreted in terms of inland water heights. Much valuable work has been carried out where heights have successfully been retrieved, and extensive validation of these heights has been performed by many researchers. This has enabled development of applications such as estimates of lake volume change. Finally, to assess the impact of a higher Pulse Repetition Frequency on inland water height retrieval, a global analysis has been made of the EnviSat 1800 Hz Burst Echoes obtained over three years from inland water surfaces. The results show that even small river targets with as few as 7 burst echoes can be successfully measured. Initial results from CryoSat2 SAR FBR data analysis over inland water are presented, giving a preview of the greatly enhanced monitoring capability possible from the next generation of SRAL altimeters.

Oceanography – Tides – Internal Tides and High Frequency Processes

FES 2012: A new tidal Model taking Advantage of nearly 20 Years of altimetry Measurements

Carrere, Loren[1]; Lyard, F.[2]; Guillot, A.[3]; Cancet, M.[4]
[1]CLS, FRANCE; [2]LEGOS, FRANCE; [3]CNES, FRANCE; [4]NOVELTIS, FRANCE

Thanks to its current accuracy and maturity, altimetry is considered as a fully operational observing system dedicated to scientific and operational applications. In order to access the targeted ocean signal, altimeter measurements are corrected for several geophysical parameters among which the ocean tide correction is one of the most crtitical. Global ocean and loading tide models GOT and FES are operationally used in present altimeter GDRs. FES is a finite elements hydrodynamic model which assimilates altimeter and in situ data, while GOT model is build as an empirical adjustement based on altimeter data of a prior atlas (such as FES).

The accuracy of tidal models has been much improved during the last 20 years. Still, significant errors still remain mainly in shelf seas and in polar regions. A new global tidal FES model is being developed taking advantage of longer altimeter time series, improved modelling and data assimilation techniques, and more accurate ocean bathymetry. Special efforts have been dedicated to the determination of accurate tidal currents and to address the major non-linear tides issue. We detail the most significant advances in the dynamic modelling, data analysis and assimilation. Finally we present the main improvements achieved compared to former releases of the FES model and the available modern global ocean tide models.

Fortnightly Ocean Tides, Earth Rotation, and Mantle Anelasticity

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The fortnightly Mf ocean tide is the largest of the long-period tides (periods between 1 week and 18.6 years), but Mf is still very small, generally 2 cm or less. All long-period tides are thought to be near equilibrium with the astronomical tidal potential, with an almost pure zonal structure. However, several lines of evidence point to Mf having a significant dynamic response to forcing. We use a combination of numerical modeling, satellite altimetry, and observations of polar motion to determine the Mf ocean tide and to place constraints on certain global properties, such as angular momentum. Polar motion provides the only constraints on Mf tidal currents. With a model of the Mf ocean tide in hand, we use it to remove the effects of the ocean from estimates of fortnightly variations in length-of-day. The latter is dominated by the earth's body tide, but a small residual allows us to place new constraints on the anelasticity of the earth's mantle. The result gives the first experimental confirmation of theoretical predictions made by Wahr and Bergen in 1986.

Observations of Storm Surges by Satellite Altimetry: Hurricane Igor off Newfoundland

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Observations of cross-shelf structure are limited. In this study we combine the Jason-2 (it concurrently passed over the Grand Banks during the Igor's passage) altimetry with tide-gauge data to study the storm surge. Altimetric observations reveal prominent cross-shelf variation of sea surface height during the storm passage, including a large nearshore slope and mid-shelf depression. A significant surge of 60 cm (25 km from the coast) observed by satellite altimetry is found to be consistent with tide-gauge measurements (about 90 cm) at nearby St. John's tide-gauge station at 2:40, September 22, 2010 UTC. The tide gauge at St. John's observed a maximum surge of 96 cm after (at 2:30, September 22, 2010) the storm passage. The maximum surge at St. John's was thought to be associated with equatorward-propagating coastally-trapped Kelvin wave, generated along the northeast Newfoundland coast hours after the storm moved away from St. John's. The e-folding scale of the Kelvin wave was estimated to be ~100 km. The study for the first time shows the utility of satellite altimetry to observe the cross-shelf features of a storm surge, providing important information for analyzing the surge characteristics and for validating and improving storm surge models.

Latest Improvements in tidal Modelling: a regional Approach

Cancet, Mathilde[1]; Lyard, Florent[2]; Birol, Florence[3]; Roblou, Laurent[2]; Lamouroux, Julien[1]; Lux, Muriel[1]; Jeansou, Eric[1]; Boulze, Dimitri[1]; Bronner, Emilie[4]
[1]NOVELTIS, FRANCE; [2]LEGOS, FRANCE; [3]LEGOS/CTOH, FRANCE; [4]CNES, FRANCE

With amplitudes ranging from a few centimetres to several meters in some continental shelf regions, the oceanic tide is a large contributor to the ocean topography variability observed by the satellite altimeters, and more particularly in the coastal areas. In most scientific applications using altimetry data, global models are used to correct the altimeter sea surface heights from the tide in order to focus on other ocean dynamics signals. The accuracy of these models is generally at the centimetre level in the open ocean. The main error sources are principally located in the coastal areas and in the polar regions, where the tidal signal is amplified and more difficult to comprehend because of the complex and often not well-documented bathymetry. Another issue is the strongly non-linear dynamics of the tide in the shelf seas.

The recent improvements in the coastal altimeter data processing now enable to retrieve better-quality sea surface heights in shallow waters. It has naturally led to the implementation of regional high resolution tidal models with the objective to more properly correct the altimeter data by increasing the models accuracy and extending the prediction spectrum, in particular with non-linear constituents. Improved digital bathymetry, higher model grid resolutions and 20-year long assimilated altimetry time series are some of the numerous improvements that benefited the regional tidal atlases construction during the last years. Firstly, we assess the accuracy and precision of some regional tidal atlases. Secondly we focus on the scientific and offshore engineering applications of these atlases and their contributions to the coastal altimeter data accuracy.

How Stationary are the internal Tides in a high resolution global ocean Model?

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[1]Naval Research Laboratory, UNITED STATES; [2]University of Michigan, UNITED STATES; [3]NASA, UNITED STATES

The stationarity of the internal tides generated in a global eddy-resolving ocean circulation model is explored using 5 years of model output. The simulated internal tide is first compared with estimates obtained from altimetric sea-surface heights. Both the model and observations show strong generation of internal tides at a limited number of "hot spot" regions with propagation of beams of energy for thousands of kilometers away from the sources. The model tidal amplitudes compare well with observations near these energetic tidal regions. Averaged over these regions, the model and observation amplitude estimates agree to approximately 18% for the 4 largest semi-diurnal constituents and 24% for the 4 largest diurnal constituents. Overall the RMS variability in the M_2 tidal amplitude is approximately .2 cm or larger over most of the Pacific and Indian Ocean. The RMS variability of the M_2 tidal amplitude can approach the mean amplitude in weaker tidal areas such as the tropical Pacific and eastern Indian Ocean, but it is small in relation to the mean amplitude over the hot spot regions. This suggests that the simulated internal tide is largely stationary over the hot spot regions. The stationarity of the simulated internal tide will be further explored in this presentation.

Building the 20-Year Altimetric Record I

Oceanography from Radar Altimetry - The Early Years (highlights)

Hausman, Jessica[1]; Beckley, Brian[2]; Haines, Bruce[1]; Leben, Robert[3]
[1]Jet Propulsion Laboratory/Caltech, UNITED STATES; [2]SGT/NASA Goddard Space Flight Center, UNITED STATES; [3]CCAR/University of Colorado, Boulder, UNITED STATES

The ERS-1, TOPEX/Poseidon, ERS-2, Jason-1, Envisat and OSTM/Jason-2 satellites together have provided over 20 consecutive years of radar altimetry. Data from these unique observing platforms have helped redefine our understanding of ocean dynamics on global scales. These missions have ushered in an era of operational near real time monitoring of mesoscale circulations, as well as advanced our understanding of ENSO, wave heights and indicators of climate change, such as global mean sea level, ice cover, lake and river levels. Before these missions were conceived, earlier radar altimeters provided convincing evidence that the oceans could indeed be successfully measured from space. Skylab was launched in 1973, and carried an experimental radar altimeter system that provided the first indication that ocean topography could be measured from space. While it operated for only short passes, the Skylab altimeter was able to capture basic geoid variations, including a dip in the sea surface that corresponded with the Puerto Rico Trench. In 1975 GEOS-3 launched with the purpose of being a geodetic mission, but also showed that it was capable of measuring large mesoscale circulation features. Then, the first dedicated oceanographic satellite mission, Seasat, launched in 1978. It furthered the understanding of mesoscale features in the oceans and, despite its short life, cemented ideas of what were possible. The Navy GEOSAT mission further demonstrated that satellite altimeters could measure the oceans with increasing accuracy and precision. In 1985, GEOSAT's primary mission phase, the Geodetic Mission (GM), provided a dense network of global observations that would improve the determination of the Earth's gravitational field and sea floor topography. The secondary mission, GEOSAT Exact Repeat Mission, provided nearly three years of global observations along the Seasat 17-day repeat ground track. That enabled declassification of the GEOSAT altimetry data and the ability to analyze the collinear data by the scientific community to further study mesoscale features and ENSO, even though the primary GEOSAT GM geodetic data remained classified at the time. All of these missions showed that altimeters were very capable of measuring sea surface height and anomalies from space. Scientists were able to track eddies, improve bathymetric measurements, tide models and much more. They were also the proof of concept needed to get modern missions like TOPEX/Poseidon and Envisat off the ground. This presentation will highlight the major contributions of these early missions and describe how they paved the way for TOPEX/Poseidon, Jason-1 and other missions, allowing for over 35 years of radar altimetry and many more to come.

The REAPER project: Bringing ERS Altimetry data set to ENVISAT standards (highlights)

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ESA's first Remote Sensing Satellite: ERS-1 was launched on July 17, 1991 and operated until June 1996, completing one year of parallel operation (Tandem Mission) with ERS-2. Launched in April 1995, ERS-2 has operated for over 16 years with all instrumentation still working well despite the loss of the on-board tape recorders and the transition to gyro-less pointing. Since the launch of Envisat in March 2002, the continuing operation of ERS-2 has provided a valuable overlap of the Radar Altimeter missions. The existing ERS Altimetry data set is known to be not fully homogenous over the two-mission lifetime, as a result of different algorithmic evolutions performed on the ERS-1 and ERS-2 ground processing chains and of changes in the RA (Radar Altimeter) and MWR (MicroWave Radiometer) sensors behaviour due to ageing effects and on-board anomalies. The aim of the REAPER project is to reprocess all available ERS-1 and ERS-2 RA and MWR data, from July 1991 through to June 2003, to produce a coherent and homogeneous long-term series that is cross calibrated and offers continuity with the Envisat RA-2 (Ku & S-band bi-frequency Radar Altimeter) mission. The use of the latest geophysical models improves the corrections applied to the range measurement. By revisiting the instrument calibration algorithms and applying retrospectively the experience gained on the effects of instrument ageing, further improvements in measurement accuracy are gained. Derivation of a new Precise Orbit solution across the 12 year period results in a significant improvement to the orbit accuracy and hence the final surface height measurements. The resulting data set will allow greater exploitation than was previously possible of the full potential of the archived ERS Altimetry data set over ocean, land and ice surfaces. This paper describes the new processing algorithms and geophysical models that are used in the reprocessing chains, and the new products that will become available. We present estimates of the improvement in measurement accuracy achieved, and show the initial results of the cross-calibration of products between ERS-1 and ERS-2 and between ERS-2 and Envisat.

Geosat and GFO: Enhancements to two Historical Altimetric Data Sets (highlights)

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Geosat, launched in 1985, and Geosat Follow-On, launched in 1998, provide unique altimetric data sets from a non-sunsynchronous 17.05 day repeat-period ground track. The final Geophysical Data Records (GDRs) from these two U.S. Navy missions have been the responsibility of NOAA's Laboratory for Satellite Altimetry.

In the intervening years the Geosat data have been enhanced several times, most notably with improved precision orbits and geophysical corrections. The original sensor data records and waveform data records have been recovered from 9-track tape for both the Geodetic and Exact Repeat Missions (Figure 1). The Geodetic Mission data have been merged and retracked, leading to major improvements in marine gravity and predicted ocean bathymetry. We are now embarking on merging and retracking the Exact Repeat Mission data, to complete the 4.5 year time series. There are ongoing efforts to extend the time series of global mean sea level by adding the Geosat measurements to those from the Topex/Jason and ERS/Envisat series of missions.

Geosat-Follow-On (GFO) suffered several hardware issues during its first two years, but ultimately provided GDRs from 2000 through 2008. New precision orbits for GFO, as well as Geosat, have been provided by NASA/GSFC based on ITRF2008 and other modeling improvements, but no full GDR reprocessing has yet been performed. The waveform data from this mission were acquired only on passes that traverse Greenland or Antarctica, but this resulted in good ascending pass coverage over Africa and descending pass coverage over North America. There is continued interest in retracking this limited set of GFO waveforms for continental hydrology studies, so we intend to produce a reprocessed GFO dataset that includes all available waveforms.

The status of the data sets from these two missions will be presented, along with a discussion of the ongoing enhancements and retracking efforts that are being made. The sampling characteristics of these missions, and the historical nature of the Geosat data from the late 1980's, continues to make them both valuable to the 25-year long altimetric data record.

Reprocessing TOPEX for the Climate Data Record (highlights)

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TOPEX/POSEIDON as the first mission in the partnership between NASA and CNES in dedicated, high accuracy ocean altimetry missions forms a crucial part of the 20 year ocean climate record. TOPEX/POSEIDON used three altimeters over its lifetime: TOPEX (NASA) Alt-A and Alt-B and the experimental CNES POSEIDON, forerunner of the Jason series. The TOPEX altimeters had certain waveform features ("leakages") that have become increasingly important as altimetry is pushed to the sub-millimeter per year accuracy level. There was also the transition from TOPEX Alt-A to Alt-B necessitated by changes in the point target response (PTR) of Alt-A, most clearly manifested by an apparent increase in significant wave height (SWH). In order to bring TOPEX data up to the standard of more recent altimeter data and to correct for waveform features and PTR changes, the TOPEX data are being retracked with newly derived PTRs from calibration data and waveform adjustments ("weights") to correct for leakages. In addition to these instrument processing differences, many advances in orbits and ancillary data have been made over the years. The plan for producing Climate Data Records consistent with the current Jason series data will be discussed.

Consistent Multi-mission Altimetry Products from SALP and RADS

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For almost 20 years, the French space agency (CNES) has been operating a multi-mission facility for managing, processing, validating and disseminating a wide range of altimetry products. The Service d'Altimétrie et Localisation Précise (SALP) was developed with a consistent multi-mission strategy, and this baseline is still used when CNES is involved in new altimetry missions, performing routine production from telemetry to Level 4 products for several missions such as Jason-1, Jason-2, ENVISAT, CryoSat-2. Thanks to this continuous effort, and to the active involvement of partner Agencies (NASA, NOAA, Eumetsat, ESA and soon ISRO), the CNES/AVISO portal is serving more than 3000 scientific user groups worldwide as well as operational oceanography services such as MERCATOR Océan and core services from the European GMES Program. At more or less the same time, the Radar Altimeter Database System (RADS) was first developed at the Delft University of Technology in order to better compare and combine altimeter data from ERS-1, ERS-2 and TOPEX/Poseidon into a single database. At the time, limited resources required condensing the data to the most essential information such as sea level, wave height, wind speed and time and location of the measurement. For the last ten years, development has continued at NOAA's Laboratory for Satellite Altimetry, while TU Delft has provided a web interface, an rsync server, and a mailing list server. Geophysical Data Records (GDRs) from nine altimeter missions (from Geosat onward) are presently incorporated into the Radar Altimeter Database System, forming the basis for a prototype Level 2 sea level Climate Data Record (CDR). Tools to produce Level 3 (and soon Level 4) products are included in the accompanying software, allowing most flexibility for scientific users. While the original design philosophy and implementation differs, both SALP and RADS have a common goal: to provide users, both expert and non-expert, with high-quality cross-calibrated harmonised radar altimeter data. The differences between the two systems are also their respective strengths: - SALP generally provides more processed higher level data in order to reach out to the large common denominator of oceanographical users - RADS aims to give expert users most flexibility in selecting alternative data corrections, allowing more "niche" uses of altimetry, yet providing software tools to do most of the work. - SALP starts with low level altimeer data, allowing full control of all parameters in the processing, including retracking, calibrations, etc., while RADS has to rely mostly on GDR-type data - While the much larger user base is to great advantage of SALP, the smaller user base allows RADS to make more regular updates, which is made most practical for users by proving rsync server access - Because SALP and RADS have a lot of overlapping users, both benefit from reports from users on the differences between them, both in data content & implementation

Benefits of the Multi-agency / Multi-disciplinary Approach

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In the early 90's, after Geosat, the ERS and Topex/Poseidon space altimetry missions radically changed the Earth Observation for all surfaces and particularly for ocean observation and studies. Since then, thanks to the sustained observation by subsequent missions like the Jason series, EnviSat, GFO, now CryoSat, both number and variety of scientific applications of altimetry have grown dramatically and a lot of operational applications have come up.

In this paper, the reasons of this success are analysed in light of this 20 year experience showing in particular how the multi-agency/multi-disciplinary approach could be one of the keys of success. From meaningful examples, the collaboration and also sometimes the competition between the contributing agencies is firstly identified as of great benefit: the involvement in an international context, the responsibility share between space and operational agencies. Then, from the past and present experiences the multi-disciplinary approach is showed as a major source of improvement, melting different and sometimes conflicting domains, trying to find the best trade-offs and gathering in a same forum all the spectrum of expertise needed to optimize the usefulness and the efficiency of the altimeter systems.

All these improvement factors are shown as crucial for building the 20 year altimeter data record and to extend it with the next generation of altimetry missions and future technologies.

Reciprocal Benefits of Multi-mission Satellite Altimetry Comparison

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In order to build a 20-year altimetric record, the cross-calibration between satellite altimetry has strongly contributed to improve the quality and the accuracy of the altimetry measurements. This paper aims at describing the main results achieved for 20 years to obtain reciprocal benefits of multi-mission satellite altimetry comparison.

The main result is the calculation of the global Mean Sea Level (MSL) on a continual basis since January 1993. Thanks to "Verification phases", during which the satellites follow each other in close succession (TOPEX--Jason-1, then Jason-1--Jason-2), the global and regional MSL biases to link up these different missions has been precisely determined. Additional strong benefits of "Verification phases" have been the detection of errors on altimetry systems of the new altimetry missions just after their launch (Jason-1 in 2002, and Jason-2 in 2008), but also errors on the reference missions. For instance, systematic geographical biases have been detected between TOPEX and Jason-1 due to the orbit calculation, but also as a result of errors on the TOPEX ground processing.

Cross-comparison with ESA missions (ERS-1, ERS-2, Envisat) have also provided a lot of information relevant for all the missions. For instance, the long-term comparisons performed between Envisat and Jason-1 highlighted a strong drift of Envisat global MSL (-2 mm/yr) which have been recently corrected. Furthermore, significant regional drifts between both missions have also been detected (+/- 3 mm/yr). Recent analyses have shown that these discrepancies were impacting the sea-level estimation for both missions. New orbit release taking into account better long-term evolution of gravity fields will correct these errors.

Through these main results, this paper highlights the main role of multi-mission cross comparison studies performed in the framework of validation activities for the future of altimetry.

Cryosphere I

The New Vision of the Cryosphere Thanks to 20 Years of Altimetry

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Altimetry is probably one of the most powerful tools for the observation of the sea ice and of ice sheet. 5 years ago, a synthesis presented in Venice, at the "15 years of Progress in Radar Altimetry" Symposium, concluded that altimetry has provided a strong new vision for ice sheet modeling. It allows mapping topography with an unprecedented precision but also balancing velocity or geothermal flux, to detect subglacial lakes and hydrological networks, to point out several physical processes such as longitudinal stresses, sliding, to test and constraint ice sheet modelling… These 15 years were also enough to provide mass balance of the Greenland and Antarctica ice sheets and to detect important ice discharge of several glaciers, such as the Pine Island one. To finish, it was concluded that altimetry was an unique remote sensing tool for sea ice thickness …Nothing yet about subglacial lake discharges, nothing about impressive acceleration of loss of mass for several glaciers of both ice sheets, little about the space and time mapping of sea ice thickness or of ice sheet mass balance. We propose here a new synthesis of our knowledge of the cryosphere thanks to 20 years of ERS and Envisat altimetry. We will focus on the most recent impressive progresses provided by these sensors.

A Reconciled Estimate of Ice Sheet Mass Balance

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There remains poor agreement between estimates of ice sheet mass balance, and the consequent global sea level contribution, as determined using the three satellite geodetic techniques of altimetry, interferometry, and gravimetry. All three methods are technically sound; the disagreement arises due to differences in their spatial and temporal sampling and the impact and accounting of fluctuations in surface mass accumulation. The IPCC have expressed concern that progress will not be made in the run up to the fifth assessment report; in their 2010 report on sea level rise and ice sheet instabilities this disagreement was highlighted as a primary emerging topic and the value of inter-comparison projects was explicitly noted. Both the scientific community and international space agencies have a vested interest in resolving this matter.

The Ice Sheet Mass Balance Inter-Comparison Exercise (IMBIE) is a first joint-initiative of the European Space Agency and the US National Aeronautics and Space Administration aimed at resolving the apparent disagreement between geodetic estimates of ice sheet mass balance. IMBIE will achieve this through a coordinated exercise where estimates of ice sheet mass balance are developed from all three geodetic techniques using a common spatial and temporal reference frame and a common appreciation of the contributions due to external signals. The project brings together the laboratories and space agencies that have been instrumental in developing independent estimates of ice sheet mass balance to date. Critically, IMBIE aims to deliver a reconciled estimate of ice sheet mass balance in time for the fifth assessment report of the IPCC. This presentation will summarise the achievement and the final conclusions of the IMBIE project, with a particular emphasis on the contribution due to satellite altimetry.

Comparison of Surface Elevation Changes of the Greenland and Antarctic Ice Sheets from Radar and Laser Altimetry

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A primary purpose of satellite altimeter measurements is determination of the mass balances of the Greenland and Antarctic ice sheets and changes with time by measurement of changes in the surface elevations. Since the early 1990's, important measurements for this purpose have been made by radar altimeters on ERS-1 and 2, Envisat, and CryoSat and a laser altimeter on ICESat. One principal factor limiting direct comparisons between radar and laser measurements is the variable penetration depth of the radar signal and the corresponding location of the effective depth of the radar-measured elevation beneath the surface, in contrast to the laser-measured surface elevation. Although the radar penetration depth varies significantly both spatially and temporally, empirical corrections have been developed to account for this effect. Another limiting factor in direct comparisons is caused by differences in the size of the laser and radar footprints and their respective horizontal locations on the surface. Nevertheless, derived changes in elevation, dH/dt, and time-series of elevation, H(t), have been shown to be comparable. For comparisons at different times, corrections for elevation changes caused by variations in the rate of firn compaction have also been developed. Comparisons between the H(t) and the average dH/dt at some specific locations, such as the Vostok region of East Antarctic, show good agreement among results from ERS-1 and 2, Envisat, and ICESat. However, Greenland maps of dH/dt from Envisat and ICESat for the same time periods (2003-2008) show some areas of significant differences as well as areas of good agreement. Possible causes of residual differences are investigated and described.

Interannual and Decadal Variability of Antarctic Ice Shelf Elevations from Multi-Mission Satellite Radar Altimetry

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It is now recognized that ice shelves exert a significant dynamic constraint on the offshore flow of ice from the large ice sheets. Recent observations of ice shelf retreat, collapse and thinning along the Antarctic Peninsula and Amundsen Sea coasts indicate that ice shelves can respond rapidly to changing atmospheric and oceanic conditions. These observations have been interpreted as evidence that climate forcing could lead to rapid changes in ice sheet dynamic flow and its associated contribution to sea level rise. Much of the recent dramatic increase in our understanding of ice-shelf processes coupling the ice sheets to climate variability comes from analyses of trends in surface elevation (dh/dt) provided by satellite altimetry. However, these analyses are usually based on short records (e.g., ERS-1, ERS-2 or ICESat) and generally ignore the interannual-to-decadal variability that overlies the trends. Thus, significant uncertainty remains as to whether the dominant forcing of ice-shelf dh/dt is related to long-term trends in climate and intrinsic ice sheet variability, or whether it is a response to interannual and decadal variability in oceanic and atmospheric circulation. To address this uncertainty we have developed a new data set of elevation-change time series for all of Antarctica's ice shelves spanning the more than two decades covered by the following satellite radar altimeter (RA) missions: Geosat (1985-1989), ERS-1 (1991-1996), ERS-2 (1995-2005), GFO (1998-2008) and Envisat (2002-present). We first develop optimal procedures for multi-satellite data integration. To the cumulated data we then apply geophysical corrections including improved ocean tide estimates, load tide, the inverse barometer effect, regional sea level rise and backscatter corrections. We also use modeled changes in firn density to seek an improved elevation correction to account for radar penetration below the surface. We show that the resulting records provide reliable long-term, quasi-continuous time series in a high-resolution grid for consistent trend and variability analysis. After clear separation of short- and long-term oscillations, we derive maps of ice shelf elevation change rates based on a >20-year time span. This allows us to investigate coherent variations and characterize the time and space patterns of change towards determining relationships with modes of climate variability.

Time Series Of Surface Height Of The Antarctic Ice Sheet From Envisat Along Track Radar Altimetry

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Envisat was placed on a 35 day repeat orbit from 2002 till October 2010. This long and regular data set allows a densely sampled observation of the Antarctic ice sheet. We processed the data along track to improve the spatial coverage while previous studies made use only of data at cross over points. We correct for poor spatial repetitivity and snow-pack changes (Flament et al., 2012). We process data each kilometre along track in order to optimise the spatial coverage. Height changes mapped over the 2002-2010 period usually vary between +15 and -15 cm per year. Comparison with ERS suggests that East Antarctica is subject to large scale changes, probably linked with atmospheric forcing (accumulation variability).

Yet in places, much larger height changes occur. In West Antarctica, we confirm the intense thinning of the glaciers of the Amundsen Sea Embayment (ASE). In particular Pine Island Glacier is observed to thin up to 250km from the grounding line and the thinning along the trunk of the glacier is accelerating. The dynamic nature of this thinning is demonstrated another time from this dataset. Other parts of the ice sheet undergo significant height changes with regard to the interannual variability in accumulation, such as Totten Glacier in East Antarctica for instance.

The high time resolution is also an asset when studying rapid events such as lakes drainage. The use of ICESat data complement the space and time sampling to yield a clear view on a cascading drainage event, upslope from the Cook ice shelf (Georges V Land, East Antarctica). To finish, we will also show a few not fully explained short scale phenomena than can be detected thanks to the higher spatial resolution.

Oceanography – Large Scale I

Multi-Decadal Sea Level and Gyre Circulation Variability in the Western Tropical Pacific Ocean

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Sea level rise with the trend > 10 mm/yr has been observed in the tropical western Pacific Ocean over the 1993-2009 period. This rate is three times faster than the global mean value of the sea level rise. Analyses of the satellite altimeter data and repeat hydrographic data along 137E reveal that this regionally enhanced sea level rise is thermosteric in nature and vertically confined to a patch in the upper ocean above the 12 deg C isotherm. Dynamically, this regional sea level trend is accompanied by southward migration and strengthening of the North Pacific Current (NEC) and North Pacific Countercurrent (NECC). Using a 1.5-layer reduced-gravity model forced by the ECMWF reanalysis wind stress data, the authors find that both the observed sea level rise and the NEC/NECC's southward migrating and strengthening trends are largely attributable to the upper ocean watermass redistribution caused by the surface wind stresses of the recently strengthened atmospheric Walker circulation. Based on the long-term model simulation, it is further found that the observed southward migrating and strengthening trends of the NEC and NECC began in the early 1990s. In the two decades prior to 1993, the NEC and NECC had weakened and migrated northward in response to a decrease in the trade winds across the tropical Pacific Ocean.

Twenty years of Satellite Altimetry: Understanding the Decadal Variability in the North Pacific Ocean - Overview

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The 20-year satellite altimetry data record is providing new insights on the nature of the ocean's role in decadal time scale climate variability. A prominent decadal mode is known as the Pacific Decal Oscillation (PDO); an interdecadal sea surface temperature (SST) variability pattern in the North Pacific, known to have links to climate variability in North America, and impacts on water resources in the western U.S. and Canada. The PDO index is classified as either a warm or cold phase according to the sign of SST anomalies along the eastern North Pacific boundary, which in turn are in opposite phase to central North Pacific SST anomalies. The PDO variability is clearly evident from satellite altimetry as a sea surface height (SSH) mode that is highly coherent with SST, both spatially and temporally. The traditional SST PDO index has more energetic short-term variability than the SSH mode, indicating that the oceanic SSH provides a more robust indicator of the longer term PDO phase changes. Satellite altimetry SSH data clearly show that the PDO was in a warm phase prior to the large 1997-98 El Niño/La Niña, and has remained in the cold phase 11 of the 14 years that have elapsed since, after a very rapid transition in 1998-99.

The focus of this paper is on the ocean dynamics associated with the PDO variability in the northeast Pacific as seen in the SST and SSH data of these past two decades of satellite altimetry, and its relationship to surface wind stress and heat fluxes. The coherency between the SST and SSH modes points toward concurrent processes governing both the surface temperature and upper ocean heat content, which are manifested by deepening of the pycnocline during warm SST anomalies. An assortment of one-dimensional upper-ocean models forced by atmospheric fluxes reproduces the large-scale SST variability pattern and amplitude quite well, but SSH variability to a much lesser extent. The SSH variability, in turn, is well represented by models of pycnocline displacement driven by Ekman pumping. Forced Rossby wave dynamics and linear damped Ekman pumping dynamics have comparable skill in reproducing the observed SSH variability. An important feature in the 20-year SSH record is the rapid PDO phase transition during 1998-99, which entailed large scale pycnocline adjustment and heat content change in the central North Pacific. Lagged regressions of geostrophic and Ekman currents against the SSH-PDO index indicate that the wind stress anomalies one to two years before the PDO mature state accounted for much of the SSH tendency, and the horizontal heat advection also contributed to the temperature variations. The importance of upper ocean currents to the upper ocean heat budget and SSH is still being investigated, but it appears that they will provide some degree of predictive skill for oceanic PDO variations.

A Statistical Analysis of Gulf Stream Variability from 20 Years of Altimetry

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Seasonal variations in the Gulf Stream were analyzed using nearly 20 years of altimetry data from Topex, Jason-1, and Jason-2. Descending pass #50, which brackets the core of the Gulf Stream between 32-39°N and 68-72°W, was analyzed in terms of absolute sea surface height, referenced to a geoid model, and sea surface height anomalies, referenced to a global mean sea surface. Indices for geostrophic velocity, baroclinic transport, and average position of the Gulf Stream were also analyzed.

The three dominant periods for these variables, based on spectral and auto-covariance analyses, are SSH: 15-21 months, 7 months, and 4 years; SSHA: 9 months, 21 months, and 5-6 months; velocity index: 9 months, 21 months, and 5 months; transport index: 11 months, 2-3 months, and 1 month; and Gulf Stream position: 21 months, 13 months, and 4-6 years.

The average annual distribution of the variables slowly increases throughout the year to late summer and early fall, quickly decreases to a minimum in winter, and increases to a secondary maximum in early spring. However, none of the seasonal time series resemble a pure sinusoid..

The Gulf Stream behaves like a strongly nonlinear system. Spectral and Principal Component Analyses of both SSH and SSHA are "pink", indicating an energetic broad-band spectra. Peak values in near-surface geostrophic velocity occur in early summer, maximum northward migration of the Gulf Stream path in August, and maximum baroclinic transport in the fall. Both the velocity and baroclinic transport modes are dominated by a summer maximum, a secondary maximum in the spring, and a minimum in the fall. The seasonal variations in velocity are weaker than for the other parameters, which may be explained by the in-phase relationship between height changes across the current and the width of the current.

The coherence calculated between the time series of GS position and the NAO index is signi cant at the 80% con dence level for periods between 9 and 18 months, and the times series are generally out of phase with each other. However, the time series of GS position and NAO index both exhibit strong non-stationary behavior.

Atlantic Climate Variability Across Scales: Ocean-atmosphere Coupling and Meridional Circulation during the Satellite Era

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Twenty years of global altimetric ocean-surface elevation fields provide unique images of both surface circulation and ocean heat content. With spatial resolution across the range of scales from mesoscale eddies to full-ocean gyres, new aspects of Atlantic circulation and climate variability can now be described.

The 20-year trend in circulation and heat content of the upper ocean is significant, and has been identified with acceleration of Southern Hemisphere subtropical ocean gyres (Roemmich *et al.* 2007) and deceleration of North Atlantic gyres, both subpolar and subtropical (Häkkinen & Rhines 2004 *et seq*.). In both cases linkages with key aspects of atmospheric circulation have been established: the acceleration of the polar vortex in the Southern Hemisphere and atmospheric blocking/storm track dynamics in the North Atlantic. This work has now been extended to suggest that atmosphere and ocean are coupled in their Atlantic Multidecadal Variability (AMV) over the entire past century (Häkkinen, Rhines & Worthen 2011).

The latest event in the ~100-year record AMV is the dramatic warming of the northern Atlantic from mid 1990s to 2012. Connections between this coupled ocean/atmosphere variability and the deep meridional ocean overturning circulation (AMOC) are complex. The warm AMOC branch has carried increasingly warm, saline waters northward from subtropics to high latitude, even to the Arctic Basin.

What makes the satellite contribution so striking is that mesoscale resolution is essential in the ocean, and correspondingly synoptic-scale resolution is essential in the atmosphere. Using new reanalysis data (Compo *et al.* 2011) we show that synoptic scale atmospheric Rossby wave breaking is coupled with warm surface ocean, and that atmospheric wintertime blocking, a dominant force in extreme weather events, follows these two. The advent of greater spatial resolution with swath altimetry will improve these results particularly at high latitudes, in boundary currents and regions of strong seafloor topographic features.

Across the breadth of the Atlantic, eddies and jets are active and essential to the process of meridional transport of heat, salt and tracers. Chelton *et al.* (2011) have established the long lifetimes of oceanic eddies, and their systematic propagation; new work shows the cores of these eddies can transport water masses over great distances. By combining altimetry with surface drifters and ARGO floats these complex relationships begin to clarify, and there is increasing evidence of strong control of even the upper-ocean circulation exerted by seafloor topography. These observations identify ocean circulation to be a 'mixture' of the broad-brush circulation captured by coupled climate models with distinct mesoscale eddy-transports inaccessible to these climate models.

Testing the Applicability of the ENSO recharge/discharge Oscillator Paradigm with Altimetry- and Model-derived Sea Level

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Four major theories have been proposed to explain the oscillatory nature of ENSO, the largest signal on interannual timescales in the tropical Pacific Ocean. These theories, however, were proposed more than a decade ago, before the recent enhanced attention given to a 'new' flavor of El Niño referred to here as central Pacific (CP) El Niño. Different structures between eastern Pacific (EP) and CP events have been found and documented by looking at the location of anomalous patterns in usual climate and biological variables (e.g., sea surface temperature and salinity, wind stress, precipitation, surface zonal currents and chlorophyll). The contrasted EP and CP ENSO features were, however, very poorly documented in terms of dynamics. Consequently, this study aims to test the applicability of one of the leading ENSO theories, the recharge/discharge (RD) oscillator paradigm, to explain the EP and CP ENSO features. In brief, the RD paradigm emphasizes that there is an inward flux of warm waters entering the equatorial band (recharge) at the onset and an outward flux (discharge) during an El Niño event. Accordingly, a key element of the RD paradigm, as well as a notable ENSO precursor, is warm water volume (WWV) and a good proxy for this is sea level anomaly (SLA).

We first show the existence of the different flavors of ENSO in the tropical Pacific during 1993-2010 in altimetry-derived SLA data using a sophisticated agglomerative hierarchical clustering (AHC) procedure. Four clusters are determined which are reminiscent of the conventional EP El Niño and La Niña, and CP El Niño and La Niña. The patterns of EP El Niño and La Niña clusters are almost symmetrical and show a zonal see-saw pattern pivoted near the eastern edge of the western Pacific warm pool (at around 180º-170ºW). This east-west tilt has been widely documented in literature. The CP El Niño cluster shows positive SLA concentrated chiefly in the central equatorial Pacific basin flanked by positive anomalies to the east and negative anomalies to the west. The CP El Niño cluster has about half the amplitude of the EP El Niño cluster. The CP La Niña cluster shows a meridional see-saw pattern with a fulcrum at around 5ºN and negative SLA over the entire equatorial band reaching up to 10ºS in the eastern basin and 20ºS in the western basin. Interestingly, this pattern is ascribed as the discharge mode during EP El Niño as it shows a mass depletion over the equatorial region and occurs only after the strong EP El Niño in 1997/98. Such a discharge mode is found quasi inexistent after the CP El Niño events. The results are confirmed using realistic modeled sea level data covering the 1958-2007 time period. Mechanisms responsible for these different signatures of SLA (and WWV) are discussed in terms of mass transports and dynamics, as well as the relevance of the RD oscillator paradigm to CP ENSO.

Building the 20-Year Altimetric Record II

The Precise Orbit and the Challenge of Long Term Stability

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The computation of a precise orbit reference is a fundamental component of the altimetric measurement. Since the dawn of the modern altimeter age, orbit accuracy has been determined by the quality of the GPS, SLR, and DORIS tracking systems, the fidelity of the measurement and force models, and the choice of parameterization for the orbit solutions, and whether a dynamic or a reduced-dynamic strategy is used to calculate the orbits. At the start of the TOPEX mission, the inaccuracies in the modeling of static gravity, dynamic ocean tides, and the nonconservative forces dominated the orbit error budget. Much of the error due to dynamic mismodeling can be compensated by reduced-dynamic tracking techniques depending on the measurement system strength. In the last decade, the launch of the GRACE mission has eliminated the static gravity field as a concern, and the background force models and the terrestrial reference frame have been systematically refined. GPS systems have realized many improvements, including better modeling of the forces on the GPS spacecraft, large increases in the ground tracking network, and improved modeling of the GPS measurements. DORIS systems have achieved improvements through the use of new antennae, more stable monumentation, and of satellite receivers that can track multiple beacons, and as well as through improved modeling of the nonconservative forces. Many of these improvements have been applied in the new reprocessed time series of orbits produced for the ERS satellites, Envisat, TOPEX/Poseidon and the Jason satellites, and as well as for the most recent Cryosat-2 and HY2A.

We now face the challenge of maintaining a stable orbit reference for these altimetric satellites. Changes in the time-variable gravity field of the Earth and how these are modelled have been shown to affect the orbit evolution, and the calibration of the altimetric data with tide gauges. The accuracy of the reference frame realizations, and their projection into the future remains a source of error. Other sources of omission error include the geocenter for which no consensus model is as of yet applied. Although progress has been made in nonconservative force modeling through the use of detailed satellite-specific models, radiation pressure modeling, and atmospheric density modeling remain a potential source of orbit error. The longer term influence of variations in the solar and terrestrial radiation fields over annual and solar cycles remains principally untested. Also the long term variation in optical and thermal properties of the space vehicle surfaces would contribute to biases in the orbital frame if ignored.

We review the status of altimetric precision orbit determination as exemplified by the recent computations undertaken by the different analysis centers for ERS, Envisat, TOPEX/Poseidon, Jason, Cryosat2 and HY2A, and we provide a perspective on the challenges for future missions such as the Jason-3, SENTINEL-3 and SWOT.

Is There a Drift in the Radiometer? 20 Years of Progress in Developing a Climate Quality Wet Tropospheric Correction from Altimetry

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Microwave radiometers have flown on all ocean altimeter missions over the past 20 years to provide a correction for the delay of the radar signal (relative to the speed in a vacuum) due the refractivity of water vapor in the troposphere. Over the years, the radiometer instrumentation has steadily improved as well as the algorithms used to retrieve wet path delay (PD) from the radiometer's brightness temperature (TB) measurements and we have correspondingly seen a reduction in the radiometer derived PD error, particularly the geographically and temporally correlated components of the error. We have also seen the emergence of new altimetry applications, including utilization of altimetry data in coastal regions and over inland water bodies which required the development of new algorithms to retrieve PD near or over land. This paper will present an overview of the evolution of the PD measurement provided by the microwave radiometers onboard ocean altimetry missions, focusing on the significant advances in algorithms and instrumentation and in particular those developments that have enabled the generation of a climate quality data record. The effort that has gone into ensuring a stable long term PD record, free from drift, is among the most important.

This year will mark the 20th anniversary of the start of the modern record of global mean sea level (GMSL) from satellite altimetry. Over the past two decades, the GMSL has risen by approximately 6cm while under the watchful eye of eight altimeter measurement systems. However, precisely monitoring the rise of the GMSL would not be possible without the careful calibration of the instruments that are a part of the altimeter measurement system. In particular, the microwave radiometers on the altimeter satellites have been shown to be one of the largest sources of error in the long term stability of the GMSL measurement.

In the mid-1990s, comparisons of Topex/Poseidon measurements with a global network of tide gauges first showed a relative drift that was eventually attributed to a drift in the Topex Microwave Radiometer (TMR). Later, drifts were identified in the radiometers on other altimeter systems. This prompted the need to develop methods to estimate and correct for the drift in the radiometers. Various methods have been developed over the past two decades including comparisons to numerical weather prediction models, stable natural Earth references and other satellite sensors. The evolution of these methods will be discussed along with an assessment of the current understanding of the residual uncertainty in the radiometer drift corrections enabled by these techniques and a perspective for the future, including instrument improvements that show promise to reduce or eliminate the need for these corrections altogether.

20 Years of altimeter Waveforms: a Review of Advantages/Drawbacks/Performances of various retracking Algorithms for various Missions and various Applications

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Since 20 years, billions of oceanic waveforms have been acquired by the successive altimeter missions: Geosat, ERS-1, Topex/Poseidon, ERS-2, GFO, Jason-1, Envisat/RA-2, Jason-2, Cryosat-2, HY-2. Precise estimates of geophysical parameters have been obtained thanks to retracking algorithms that fit an analytical model to the measured waveforms. Different teams in charge of this specific processing have considered, implemented and validated many different approaches depending on the mission characteristics they have to account for and depending on the applications they want to serve.

We propose in this paper to review the retracking algorithms that have been implemented by the different space agencies (CNES, NOAA, NASA, ESA, ...) with the aim to highlight their rational, advantages, drawbacks, discrepancies and more generally performances.

A special focus will be given on range and significant wave-height noise levels over oceans with the aim to clarify which oceanic scales can reasonably be solved/unsolved with conventional altimeter including the future Saral/AltiKa instrument and explaining/justifying the interest of noise level reduction especially when moving to SAR mode measurements.

Continued Progress towards A Next-generation Sea State Bias Correction Including Global Wave Model Data

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The sea state bias is a cm-level altimeter range correction designed to accurately account for unresolved ocean wave field impacts within each altimeter footprint. Operational solutions still rely largely on satellite-based empirical forms that present some drawbacks because of two central factors. First, altimeter along-track range, sea state and wind estimates are all derived from retracked waveforms and therefore contain correlated errors that hinder robust geophysical wave impact study and correction. Secondly, altimeter wave measures are used by default, while the requisite nonlinear ocean gravity wave information is more likely related to a wave height-slope cross skewness term. Despite these fundamental challenges, significant progress has recently been made leading to improved sea state bias correction.

This talk will review current SSB models in use across the satellite array and key issues related to the uncertainties and offsets of this correction will be reported. Steps needed to overcome several remaining challenges to improved and cohesive multi-mission corrections will be addressed. Error budget implications and the impact of correction inaccuracies upon on the scientific investigation of coastal zone ocean circulation, mean dynamic topography, and sea level rise will be discussed.

From conventional LRM Ku Band to new Technologies (SAR Ku Band, Ka Band): expected Performance improvement and potential Challenge to seamlessly merge them with classical Ku Datasets for ocean Applications.

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Since early 90', satellite altimetry has proven to be a valuable source of data for a broad range of applications. Looking beyond the missions in operational service today, future satellites will need to provide better spatial and temporal coverage so that we can study further near the coasts or mesoscale variations and other phenomena more closely. If the Ku band conventional pulse limited altimeters have been largely used since more than 20 years, recently launched (CryoSat) or under development (SARAL/altika, Sentinel-3, Jason-CS) missions are using new technologies that should lower the measurement noise level by a factor close to 1.5.

The nadir looking SAR altimeter concept has been studied in parallel in ESA and the US since the mid 1990s. This concept is now implemented in SIRAL instrument operating on board Cryosat-2 mission launched early 2010. Although this mission is dedicated to ice topography observations, this novel altimeter concept can be very advantageous for observation of ocean surfaces, as it promises improved altimetric precision and better along-track resolution than conventional pulse limited altimeters. This mode will also be used on Sentinel3 mission and is envisaged on Jason-CS as well. Several studies are ongoing to develop and test suitable processing algorithms for this new altimeter mode.

The mono-frequency Ka-band (35.75 GHz) radar altimeter is the main part of AltiKa instrument. The main advantage of this higher frequency altimeter (Ka versus classical Ku/C altimeters) are :

- the reduced altimeter footprint that leads to a better spatial resolution,
- an enhanced bandwidth (500 MHz), which leads to higher vertical resolution,
- and from the increased PRF (4 kHz), as at Ka band the pulse decorrelation is more rapid.

Thus, globally, an error budget improvement is expected. However, Ka-band has also drawbacks, mainly linked to its higher sensitivity to rainy and cloudy conditions.

This paper will focus on the expected performance improvement and potential challenge to seamlessly merge those new data sets with classical Ku datasets for ocean applications. In particular, recent CryoSat in orbit lessons learnt will be presented, including the reduced SAR mode (ie equivalent LRM mode).

Cryosphere II

Sea Ice Thickness and Ice Volume from CryoSat2

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Arctic sea ice has undergone major changes in recent years but there remains much uncertainty about its ultimate fate, in particular the timing of an ice-free Arctic in summer. Although satellite measurements of ice extent are well established, wide-area measurements of sea ice thickness are key to understanding the fate of Arctic sea ice cover in the future. Satellite altimeters can provide direct measurements of sea ice freeboard from which sea ice thickness can be calculated. We present the first calibrated data on sea ice thickness from Cryosat-2, validated by in situ and aircraft data. We also present the first estimates of ice volume from CryoSat compared with a state of the art sea ice model. We describe the primary uncertainties for sea ice thickness retrieval, and outline strategies for addressing these in the future.

Arctic Ocean Sea Ice Freeboard Heights and Dynamic Topography from CryoSat and ICESat

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With the increased orbit inclination, CryoSat has for the first time allowed the measurement of sea ice freeboard and ocean heights from satellite altimetry north of 86°N, and provide a continuation of the earlier ICESat measurements south of this latitude.

In the presentation we use 1 year of CryoSat data to estimate sea ice freeboard heights and ocean dynamic topography. The method combines a geoid model with a lowest-level filtering algorithm, taking into account CryoSat waveform parameters, to estimate the sea surface height. The resulting freeboard heights and mean dynamic topography (MDT) are compared to earlier ICESat-based results, showing a good agreement for MDT when converted to a common reference frame and inter-satellite biases are removed. CryoSat sea ice freeboard heights, albeit relatively noisy, confirm main sea ice thickness features.

To obtain an estimate of the errors involved in the method used here, CryoSat data are validated by direct comparison to high resolution airborne radar (ASIRAS) and laser scanner (ALS) heights obtained along transects in the Arctic Ocean from ESA CryoVEx 2011 and 2012 campaigns.

ALTIBERG, Building up a 20-year Database of Small Icebergs

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Interest for icebergs and their possible impact on southern ocean circulation and biology has increased during the recent years. If tabular icebergs are routinely tracked and monitored using scatterometer data, the distribution of smaller icebergs (<2-3km) is still largely unknown because of the difficulties to detect them operationally using conventional satellite data. Tournadre et al (2008) showed that small icebergs can be detected using 20 Hz altimeter waveforms. The method of detection has been improved to allows the estimate of the iceberg surface and the distribution of the ice volume on a monthly basis. The Jason-1 archive covering the 2002-2010 period has been processed using this method. The small iceberg database for the southern ocean gives an unprecedented description of the small iceberg distribution at unprecedented time and space resolutions. The size follows a log-normal distribution with an overall mean diameter of 713m. It has a strong seasonal cycle reflecting the melting of icebergs during the austral summer. The total volume of ice has a annual mean value of about 400~Gt, i.e. about 35\% of the volume of tabular icebergs and can play a significant role in the injection of meltwater in the ocean. The ice volume distribution presents a very high spatial and temporal variability which is very contrasted in the three ocean basins (South Atlantic, Indian and Pacific oceans). The analysis of the relationship between small and tabular icebergs shows that a majority of small icebergs are directly associated with the tabular ones but that vast regions exists where the transport of ice is done only by the smaller ones. The ALTIBERG project sponsored by CNES aims at creating a small icebergs database covering the 1992-present period. Indeed the detection method based on purely geometrical considerations can be applied with small modification to the analysis of any radar altimeter waveform. The Topex/Poseidon, Jason1-2, Envisat archives will be processed to generate a 20-year small iceberg climatology including iceberg density, ice volume etc.. This data set will be made available to the community for climatological studies, numeicial ocean circulation modeling, wave forecasting etc..

CryoSat: ESA's ice Explorer Mission: Status and Achievements

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CryoSat-2 was launched on the 8th April 2010 and it is the first European ice mission dedicated to monitoring precise changes in the thickness of polar ice sheets and floating sea ice over a 3-year period. Cryosat-2 carries an innovative radar altimeter called the Synthetic Aperture Interferometric Altimeter (SIRAL) with two antennas and with extended capabilities to meet the measurement requirements for ice-sheets elevation and sea-ice freeboard. Initial results have shown that data is of high quality thanks to an altimeter that is behaving exceptional well within its design specifications.

The first data was released to the scientific community in February 2011 and since then, products have been systematically distributed to more than 200 Principal Investigators and used by more than 500 scientists worldwide.

Scope of this paper is to describe the current mission status and the main scientific achievements since the start of the science phase. Topics will also include programmatic highlights and information about the extension of the mission data portfolio to include the new ocean products.

Oceanography – Large Scale II

The Coherence and Impact of Meridional Heat Transport Anomalies in the Atlantic Ocean Inferred from Observations

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Changes in the meridional transport of heat and in oceanic heat storage are important for understanding climate variability and prediction. Observations of thermosteric sea level (TSL) from hydrographic data (including Argo), equivalent water thickness (EWT) from GRACE gravity data, as well as altimetric sea surface height (SSH) anomalies, are used to construct budgets of heat and mass for the Atlantic Ocean from 31S to 67N and to infer changes in the meridional transport of heat. Time-varying thermosteric and mass contributions to sea level are predicted using surface heat and freshwater flux anomalies in each of seven regions; discrepancies between the modeled and observed sea level components, as well as the total SSH anomaly,are used to infer lateral heat and mass convergences. Given reasonable estimates of the model and observation errors, the "unknown control" version of a Kalman filter creates both smooth time series of sea level anomalies and a smooth residual that represents heat and mass convergences. Regional convergences are summed to estimate meridional heat transports for 1993-2010 within estimated errors. The analysis reveals that meridional heat transport (MHT) is coherent between 31S and the separated Gulf Stream and that increases in MHT are accompanied by increases of heat loss through surface fluxes in the subtropical gyre. The inferred MHT reproduces both in timing and in magnitude the 2009 drop and subsequent reversal in 2010 seen in the RAPID/MOCHA observations at 26N. The analysis also reveals previous anomalies, with values as large as 0.5PW in the South Atlantic in 1999. An intensification of MHT anomalies toward the south and a correlation of MHT with the Antarctic Oscillation suggest a southern source for the coherent MHT anomalies.

Relation Between PDO and Basin-scale Ocean Circulation Variations

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Many model efforts have been made to examine the link between the Pacific Decadal Oscillation (PDO) and the large-scale ocean and atmosphere variations. Previus studies have found that the leading satellite SSH principle component time series, the PDO SSH index, is a more robust indicator of the PDO state than the SST index in the North Pacific. Thus, the two-decade-long satellite SSH record provides a great opportunity to investigate the relation between the decadal variability and the basin-scale ocean circulation variations. The power spectrum of the 20-years-long SSH anomalies shows pronounced low-frequency ($>=$ 10 years) variability and shows no significant El Niño-Southern Oscillation (ENSO) peak, implying no significant ENSO impact in the PDO SSH index.

Lagged regressions of the SSH tendency, scatterometer wind stress curl, the satellite-derived ocean currents, and their associated lateral heat flux divergence against the PDO SSH index shed light on the responsible oceanic processes for the PDO. Particularly, we separated the geostrophic and ageostrophic (Ekman) currents to examine their relative contribution in the oceanic adjusting process. Preliminary results show that the wind stress curl anomalies one to two years before the PDO mature state accounted for much of the PDO SSH tendency, and the geostrophic heat flux divergence is responsible for the PDO SST variations. These time lead and lag relations between the PDO SSH index and the ocean currents help assess the predictive skill of the large scale ocean currents in the climate PDO signal.

On the North Atlantic Subpolar Gyre Variability as Revealed by Altimetry and the OVIDE Data Set

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The North Atlantic subpolar gyre plays an important role in the Earth's climate since it is where deep water masses constituting the lower limb of the Meridional Overturning Circulation (MOC) are formed. Here we discuss the gyre and overturning circulations, and the heat flux variability as quantified from a joint analysis of hydrographic and velocity data from six repeats (1997-2010) of the Greenland-to-Portugal A25-Ovide transatlantic section, satellite altimetry, Argo and observations from moorings. For each repeat of the A25-Ovide section, the full-depth absolute circulation and transports were assessed using an inverse model constrained by ship-mounted Acoustic Doppler Current Profiler data and by an overall mass balance. The transports thus obtained are in close agreement with those estimated using altimetry data to constrain the inverse model, as well as with a time series of the East Greenland Irminger Current transport derived by combining altimetry data with in situ current measurements from a moored array. The circulation patterns obtained from ship-based observations at the A25-Ovide line revealed remarkable transport changes in the whole water column and evidenced large variations (up to 50% of the lowest value) in the MOC intensity, computed in density coordinates. The magnitudes and time scales of the MOC variability in 1993-2011 are then evaluated using a MOC index built upon altimetry and Argo. The MOC index time series, validated by the good agreement with the A25-Ovide data-based estimates, exhibits a decline of 2 Sv in the MOC intensity between 1993 and 2010 as suggested by a linear regression. The A25-Ovide data showed that the heat transport across the section is linearly related to the MOC intensity. This

allowed us to use the 1993-2011 time series of the MOC to derive an associated 1993-2011 time series of the heat transport across the A25-Ovide section.

The Indonesian Throughflow Response to Indo-Pacific Climate Variability

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The Indonesian seas play a unique role in providing the only open pathway for inter-ocean exchange between the Pacific and Indian Ocean basins at tropical latitudes. As such, the Indonesian Throughflow (ITF) is a significant component of the global thermohaline circulation, and plays an important role in the heat and freshwater budget of both the Pacific and the Indian Oceans. The 2003-2006 INSTANT program provided the first simultaneous full-depth velocity and transport measurements in the major inflow and outflow passages of the ITF. While the three-year time series alone is not sufficient to comprehensively resolve the interannual signal, significant transport variability during the INSTANT period was linked to the large-scale climate modes of ENSO and the Indian Ocean Dipole (IOD). However the relatively short record made it difficult to separate the competing remote influences from the IOD and ENSO on the ITF transport. This study will highlight the development of proxy techniques for monitoring interannual ITF transport variability using the remotely-sensed altimeter data. The focus is on the three outflow passages of Lombok, Ombai and Timor, where direct INSTANT velocity and pressure-gauge measurements are available to help mold and ground-truth the algorithm needed to convert the proxy data to ITF transport information. The resulting 20-year time series shows strong interannual ITF variability that is related to Indo-Pacific climate variations driven by distinctive processes associated with both ENSO and the IOD.

Sea Level, Bottom Pressure and the Dynamics of Large-Scale Interannual Variability in the Southern Ocean

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Sea level (SL) variability at interannual and longer periods is often interpreted as representing changes in steric height of either thermal or haline nature. The implicit assumption of negligible variability in ocean bottom pressure (OBP) is, however, not always correct. Analyses of SL and OBP records as well as data-constrained model estimates reveal several regions in the Southern Ocean of enhanced interannual variability, with OBP magnitudes being at least half of those of SL on large spatial scales (~1000 km). The amplified OBP variability is associated with the large-scale response to wind forcing in regions with typically weaker gradients of ambient potential vorticity. Despite those weak gradients, motions against them still play a role in balancing the wind vorticity input. Additionally, and contrary to the dominance of barotropic dynamics at subannual timescales, baroclinic effects gain more importance at interannual periods, and OBP and SL variability are not always well correlated. Our results suggest a complex relation between SL and OBP as a function of time and spatial scale, with topographic controls playing a role in several regions, and provide a cautionary tale on how to interpret long period SL changes in terms of subsurface ocean properties.

Surface Geostrophic Circulation of the Mediterranean Sea Derived from Drifter and Satellite Altimeter Data

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Drifter observations and satellite-derived sea surface height data are used to study quantitatively the surface geostrophic circulation of the entire Mediterranean Sea for the period spanning 1992-2010. After removal of the wind-driven components from the drifter velocities and low-pass filtering in bins of 1° x 1° x 1 week, maps of surface geostrophic circulation (mean flow and kinetic energy levels) are produced using the drifter and/or satellite data. The mean currents and kinetic energy levels derived from the drifter data appear stronger/higher with respect to those obtained from satellite altimeter data. The maps of mean circulation estimated from the drifter data and from a combination of drifter and altimeter data are however qualitatively similar. In the Western Basin, they show the main pathways of the surface waters flowing eastward from the Strait of Gibraltar to the Sicily Channel, and the current transporting waters back westward along the Italian, French and Spanish coasts. Intermittent and long-lived sub-basin scale eddies and gyres abound in the Tyrrhenian and Algerian seas. In the Eastern basin, the surface waters are transported eastward by several currents but recirculate in numerous eddies and gyres before reaching the northward coastal current off Israel, Lebanon and Syria and veering westward off Turkey. In the Ionian Sea, the mean geostrophic velocity maps were also produced separately for the two extended seasons and for multi-year periods. Significant variations are confirmed, with seasonal reversals of the currents in the south, and changes of the circulation from anticyclonic (prior to 1 July 2007) to cyclonic, and back to anticyclonic after 31 December 2005.

The Wind Driven Spin-up of the Beaufort Gyre from Satellite Radar Altimetry

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The Arctic Ocean's freshwater budget comprises contributions from river runoff, precipitation, evaporation, sea-ice and exchanges with the North Pacific and Atlantic. The consequent storage of >70,000 km^3 of freshwater reduces the salinity of upper-layer seawater, which is separated from underlying warm, saline water by a strong halocline. Spatially and temporally limited observations show that the Arctic Ocean's freshwater content increased over the last few decades, predominantly in the west, and that freshwater entering the North Atlantic decreased by a similar amount. Models suggest that wind-driven convergence drives freshwater accumulation, but there are no continuous observations of changes in sea surface height (SSH) or halocline depth associated with this mechanism. Here we present results, from our recent publication (January, 2012), showing the wind-driven spin-up of the Beaufort Gyre from continuous satellite measurements of SSH between 1995-2010. We observe a positive SSH trend and show that the trend in the wind field has a corresponding spatial pattern, indicating that wind-driven convergence controls freshwater variability. We calculate a freshwater increase of 8000 ±2000 km^3 over the Western Arctic, in keeping with hydrographic observations. A reversal in the wind field could spin-down the Beaufort Gyre, releasing this freshwater to the Arctic Ocean and/or the North Atlantic. We will then update the SSH time series to show the evolution of this feature to 2012, to investigate if any further change has occurred since publication.

Building the 20-Year Altimetric Record III

Absolute Calibration of the TOPEX/POSEIDON and Jason Measurement Systems: Twenty Years of Monitoring from Dedicated Sites

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Dedicated calibration sites provide the foundation of the 20-yr calibration program underpinning the success of the combined TOPEX/POSEIDON (T/P) and Jason missions. Located along the 10-day repeat ground track shared by these missions, these sites are carefully instrumented to provide an independent (in-situ) determination of sea-surface height (SSH) relative to the geocenter. The absolute (geocentric) in-situ observations provide the basis for calibrating the altimetric SSH measurements made by the satellite as it overflies each location every 10 days.

The earliest examples of the overhead altimeter calibration concept are the pioneering Bermuda experiments for the GEOS-3 (1976) and Seasat (1978) altimeters. Launched in 1991, the ERS-1 satellite used the Acqua Alta oceanographic tower, 16 km off the coast of Venice, to provide a means of absolute calibration. On the heels of ERS-1, the T/P satellite was launched in 1992 with the objective of accurately measuring the elusive large-scale circulation of the global oceans. Underlying this objective was a set of stringent requirements on the satellite measurement system, and an accompanying in-situ calibration program to verify the performance post-launch. The 10-d repeating ground track was designed to directly overfly two dedicated calibration sites: the Harvest oil platform located 10-km off the coast of central California, and the tiny (1.2 km^2) Lampione Islet between Sicily and Tunisia. A third dedicated site was established in Bass Strait (between mainland Australia and Tasmania), and provided fundamental calibration information in the Southern Hemisphere.

The Harvest and Bass Strait sites continue to operate today, and have supported two decades of uninterrupted monitoring of the T/P mission and its Jason successors. The original T/P installation at Lampione was replaced in 1998 by a permanent, regional calibration experiment centered at Cape Senetosa (Corsica), which is entering its 15th year of continuous operation. Finally, a permanent calibration facility at Gavdos (Greece) was established in 2002, and also features a regional configuration suited for use on a variety of altimeter missions.

We provide in this paper a retrospective on the 20-yr absolute calibration experience for the T/P and Jason missions. We focus in particular on the significance of the SSH bias estimates, and how they have lent insight on important errors in the science algorithms for T/P and the Jason missions. We also address the impact of correlated errors at the geographically diverse calibration sites, and discuss the role of absolute calibration in verifying the emerging record of global sea level change from altimetry.

Altimeter Drift Estimation: Past, Present and Future

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Back in the late 1980's, in the days of Geosat, Klaus Wyrtki first suggested using the global tide gauge network to provide a "datum" for satellite altimetry measurements. In this presentation we will review the development of the method over the 20+ years of precise satellite altimetry in order to give the historical context. We will then give a description of the present state of the art, including evaluations of multiple altimeter datasets from multiple research groups. The emphasis in this section is on the value of inter-comparisons. We will conclude with a summary of the most recent improvements to the method, which include substantially better land motion corrections at the tide gauge locations, a significant expansion in the number of tide gauges used in the analysis, and the inclusion of reference frame uncertainties in the statistical formalism. The bottom line for this last section is an assessment of the prospects for reducing the error bar in our estimates of the global sea level rise rate.

Development of the NOAA Sea Level Climate Data Record

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Considering the tremendous social implications if an accelerated rate of sea level rise were to be sustained, evaluations and interpretations of the sea level will increasingly be needed to provide information relevant and useful to decision makers, stakeholders, and the public. Because of their demonstrated stability and unique coverage, sea level observations from altimetry are essential to building a climate data record (CDR). While satellite radar altimetry is one of the most complex forms of remote sensing, over the last 20 years, it has achieved levels of accuracy and stability in observations of sea level necessary to meet or exceed the requirements for a GCOS Essential Climate Variable. A key factor necessary to demonstrate the maturity of a climate data record is an observation strategy designed to reveal systematic errors through independent cross-checks, open inspection, and continuous interrogation. For satellite radar altimetry, the observation strategy includes a rigorous inter-satellite calibration and calibration with a global network of tide gauges.

Using the Radar Altimeter Database System (RADS) as a platform, NOAA's Laboratory for Satellite Altimetry is producing and evaluating three related prototype CDR products. The first is a Level-2 product of sea level anomalies at observed locations. The remaining two products, derived from the Level-2 product, are global and regional mean sea level time series and regional trend estimates at 1º x 1º resolution. These datasets will be produced in CF 1.6-compliant NetCDF-3, documented by an Algorithm Theoretical Basis Document (ATBD), archived at the NOAA National Oceanographic Data Center, and provided to the community via a number of standard protocols.

Here we re-evaluate the calibration and validation of observations from both the current constellation of altimeters and legacy missions that contribute to the NOAA CDR. We present a joint analysis of global and regional sea level from seven altimeter missions: TOPEX, ERS-1, ERS-2, GFO, Envisat, Jason-1, and Jason-2. We will review the current state of knowledge of the altimeter record, estimates of the relative biases between missions, and an inventory of known inconsistencies among missions. We will also present an analysis of tide gauge calibrations for the seven altimeters, which provide an invaluable independent check and the ability to isolate subtle but significant long-period signals.

ESA's Sea Level Climate Change Initiative

Larnicol, Gilles[1]; Timms, Gary[2]; Ablain, Michael[1]; Stammer, Detlef[3]; Johannessen, Johnny[4]; Faugère, Yannice[1]; Cipollini, Paolo[5]; Roca, Monica[6]; Rudenko, Sergei[1]; Fernandes, Joana[7]; Balmaseda, Magdalena[8]; Knudsen, Per[9]; Benveniste, Jérôme[10]
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The presentation aims to provide an overview and current status of the Sea Level project of the ESA Climate Change Initiative (CCI) that has started in july 2010. The main objective of this project is to produce and validate Sea Level Essential Climate Variable (ECV) product. It represents the first phase of the ESA CCI where main objectives are, first, to involve the Climate Research community which is the main user of the Sea Level ECV to improve the understanding of their needs and thus to ensure a perfect consistency between the need and the future development and improvement of the altimeter processing system. One other key objective is to develop, test and select the best algorithms in order to produce high quality sea level products for climate applications which should be assessed. A particular effort will be done to collect information on the quality and error characteristics of the Sea Level ECV product through the involvement of independent climate research groups.

This talk will be the first opportunity to officially present the CCI Sea Level ECV product and the related algorithm improvements.

DUACS: Data Fusion and High Resolution Products

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In 1997 the first homogeneous and user friendly Sea Level data set based on TP and ERS1 & 2 missions were released to the scientific community: from this date, it was not necessary anymore to be an altimetry expert to use sea level time series. This was the beginning of the DUACS story, a long and sucessful story.

The multimission processing of altimeter data was developed by CLS in 1997. DUACS (Data Unification and Altimeter Combination System) has then been integrated to the CNES multi-mission ground segment Ssalto in 2001, and it is maintained, upgraded and operated with funding from CNES/SALP project with shared costs from EU projects (MFSTEP, MERSEA, ECOOP, and MyOcean 1&2). Since then, all the altimeter missions from all the Space Agencies have been successively integrated in the system as soon as the data have been made available and assessed: GFO, Jason-1, Envisat, Jason-2 and recently Cryosat-2. The Duacs system processes the Level2 altimeter product, or (GDR, IGDR or OGDR) to provide a consistent and homogeneous catalogue of products in Near Real Time (NRT) and Delayed time (DT) . In Near Real Time, the system's primary objective is to provide operational applications and climate forecasting projects with directly usable high quality altimeter data from all missions in operations. In DT, it is to maintain a consistent altimeter climate data record using the state-of-the-art recommendations from the altimetry community.

The number of user constantly increased over the last 15 years and today the Duacs products are used around the world by about 1000 teams. As the knowledge of altimetry processing has been refined and as the oceanography needs has evolved the system has continuously been upgraded to increase the production frequency and to improve the resolution of the products and their accuracy. Today, the DUACS system is a system that responds to various needs as the provision of NRT altimetry products for monitoring and forecasting centres. Concerning the delayed time product, the DUACS system regularly produces a complete reprocessing of the whole dataset very useful for the scientific community. At the end of this year, a reprocessing of the 20 year of data, representing today a total of about 60 years of cumulated data, will take into account the latest orbit standards GDR-D for most of the mission, reanalysed meteo fields to compute the pressure derived correction, as well as all the recently released correction from CNES and ESA reprocessing projects and Climate Change Initiative projects. Finally, specific efforts have also been brought recently on another important aspects, the regional processing of altimetry: in the past year three new regional products (Mozambic, Europe, Arctic) with dedicated processing and resolution have been released, improving the quality and allowing the users to access to finer mesoscale structures.

Oceanography – Wave and Wind

Assessment of Two Decades of Altimeter Wind and Wave Products

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The prospect of global observations of surface winds and waves gave a significant stimulus to wave model development in the 1980's, while the need to have reliable wave predictions stimulated the development of operational altimeters that could provide accurate wind and wave products. Over the past two decades there has been a continuous interplay between ocean wave forecasting and altimeter sea state products resulting in improvements in both. Altimeter sea state data are presently used in the wave model analysis in the wave forecast verification, in the monitoring of the quality of the modelled surface wind and in obtaining global wave height and wind speed climatology.

ECMWF was involved in the validation of the near real time (NRT) ERS-1 altimeter wind and wave products shortly after its launch in July 1991. Comparison of ERS altimeter wind and wave products with the corresponding ECMWF fields identified problems in the ERS wind speed and significant wave height (SWH) retrieval algorithms, which were alleviated quickly thanks to the strong interaction between the wave model community and ESA. The good quality attained thereafter, encouraged the efforts to assimilate the SWH data in the ECMWF global wave forecasting system. This was achieved in August 1993 and since then it has become an important component of the ECMWF forecasting system. ERS-1 SWH data were replaced by the corresponding ERS-2 products in May 1996 which, in turn, were replaced by those of ENVISAT in October 2003 after the loss of ERS-2 global coverage. The availability of NRT Jason-1/2 altimeter data resulted in the assimilating of their SWH data into ECMWF wave model in February 2005 and March 2009, respectively.

Altimeter wind speed is not used in data assimilation at ECMWF since their impact would be small compared to that of scatterometers which have wide swath. Instead, altimeter wind speed is used for monitoring the model performance and for the validation of new model developments. The use of altimeter wind and wave data during the past two decades will be summarised and their impact will be assessed.

Contribution of Satellite Altimetry to Wave Analysis and Forecasting

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During the last two decades, the performances of numerical wave prediction models have significantly improved in term of wave analysis and forecasting, thanks to a better quality of the forcing wind fields associated with an increased spatial resolution, to the refinement of numerical wave model with improved physics package and to the assimilation of satellite data. Before end of 2012, a fourth satellite altimeter, SARAL-Altika, would join the existing constellation of three satellite altimeters already in operation, on board ENVISAT, JASON-1 and JASON-2. The positive impact of such constellation in numerical wave model forecasts at global scale has been established. Also, altimeter data have been used to calibrate and validate wave models, including in extreme wind conditions. Some of the forcing wind fields used are based on blended winds from scatterometers and numerical weather prediction models, allowing a larger spatial variability as expected in extreme wind conditions. Studies about such conditions are going on and will be continued in the next years. Satellite data are also expected to be valuable to validate coastal high resolution models, because very few in situ data are available in most places. Thanks to their global coverage, altimeter data are also very useful for assessing the impact of other satellite data for wave analysis and forecasting. In particular, the usefulness of Advanced Synthetic Aperture Radar (ASAR) for such purpose has been investigated by using altimeter data and is still subject to investigation because of recent wave physics improvements. Finally, wind and wave information from altimetry has become valuable also for wave monitoring by marine forecasters and should be used more and more widely in the future.

Hydrology and Land Processes I

Monitoring Ice and Snow Regime of Eurasian Lakes and Inland Seas from Satellite and In Situ Observations

Kouraev, Alexei
LEGOS, FRANCE

We present studies of ice and snow cover of continental water bodies using the synergy of more than 15 years-long simultaneous active (radar altimeter) and passive (radiometer) observations from radar altimetric satellites (TOPEX/Poseidon, Jason-1, ENVISAT and Geosat Follow-On) complemented by SSM/I passive microwave data. Five largest Eurasian continental water bodies - Caspian and Aral seas, Baikal, Ladoga and Onega lakes are selected as examples. An ice discrimination approach based on a combined use of the data is presented, as well as validation of this approach using in situ and independent satellite data in the visible range. We then analyse the long-term evolution of ice conditions for these lakes and inland seas using historical data and recent satellite observations.

We also address another interesting phenomenon - formation of giant rings on Baikal Lake ice. These rings (diameter 5-7 km, thickness of dark layer - 1 - 1.8 km) have almost perfect circular shape. The rings have been observed since the early 1970ies by satellite imagery in various regions of the lake. We present several existing hypotheses of the origin of these rings and discuss strengths and weaknesses of each hypothesis. We present observation of the formation, development and disappearance of these rings using various satellite data. We discuss the conditions needed to create and maintain these rings, the timing of and duration of their existence, as well as horizontal and vertical structure of ice and snow cover before and during the appearance of rings.

This research has been done in the framework of the Russian-French cooperation GDRI "CAR-WET-SIB", French CNES TOSCA AO, and FP7 "MONARCH-A" project.

Adaptive Retracking of Jason-1 Altimetry Data for Inland Waters on the Example of the Volga Reservoirs

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One of the recent applications of satellite altimetry originally designed for measurements of the sea level is associated with remote investigation of the water level of inland waters: lakes, rivers, reservoirs. In the open ocean conditions geophysical parameters are retrieved with very high accuracy, because solution of the re-tracking inverse problem is based on the strong a-priory information about the wave form of the averaged telemetric impulse given by Brown's formula. Since for the case of inland waters, the telemetric impulse is strongly contaminated by reflections from the land, this a-priory information is not applicable. Then, errors in the water level retrieved from the altimetric measurements are enormous, as we demonstrate on the basis of comparison of ground measurements of the water level of Gorky Reservoir of the Volga River and all available along track 10Hz TOPEX/Poseidon and 20Hz Jason altimetry data over the reservoir area. These conditions are typical, for example, for the majority of reservoirs of the Volga river cascade (with one exception, Rybinskoe Reservoir). Under these conditions only a few telemetric impulses fit the validity criteria, which cause a severe loss of data.

To provide new a-priory information for the re-tracking algorithm, a theoretical model of a telemetric impulse scattered by a statistically inhomogeneous surface was constructed. For the model of the terrain in the vicinity of Gorky Reservoir, the model represents the main typical features of the waveform examples, and the modeled waveforms are in good agreement with the Jason-1,2 waveforms for the same area. It was shown that for the Gorky Reservoir the retracking algorithm based on the detection of the beginning of the leading edge of telemetric impulses is preferable for correct assessment of variations of water level in Gorky Reservoir. Comparing of the data with in situ measurements of the water level of Gorky and Rybinsk Reservoirs shows that re-tracking dramatically increases the number of data involved in monitoring and significantly improves measurements of the water level. Correlation of in-situ and altimetry water level measurement after re-tracking increased from 0.3 to 0.9 for Gorky reservoir and from 0.9 to 0.99 for Rybinsk reservoir.

In August-September 2011 the first series of ground experiments were carried out at the Gorky reservoir directed to calibration of significant wave height in the algorithm of altimetry data re-tracking adapted to the conditions of an inland water body. Data on surface wave spectra and probability distribution function of waver elevation in water waves were obtained. Peculiarities of wind surface waves in inland water bodies and possibilities of significant wave height retrieval from the satellite altimetry data are discussed. General principals of retracking algorithms for complex areas based on taking into account statistical inhomogeneity of the reflecting surface adjusted to a certain geographic area.

Analysis and Retracking of Altimeter Waveforms for Hydrological Purposes

Mercier, Franck; Amarouche, Laïba; Thibaut, Pierre; Vernier, Anne
CLS, FRANCE

Over surfaces with homogeneous topography and reflectivity, such as oceans, altimeter waveforms are usually easily modeled with Brown theory and efficient state of the art retracking algorithms have been developed to reach the mm accuracy. However, millions of waveforms have also been acquired over non-ocean surfaces, such as continental water bodies. Over these hydrological targets, that are also of primary importance for climate monitoring studies for example, the waveforms are much more complex since they contain information (i.e. reflected energy) coming from both the water bodies and the surrounding, possibly rugged, terrain. Altimeter waveform may thus be distorted, or multi-peaked. We recently developed a new retracking algorithm specifically dedicated to multi-peaked waveform. The basic principle of this algorithm is to use an a priori estimation of the surface height of the target that allows focusing on the appropriate peak within the waveform. Promising results have been obtained over the Amazon basin, with noticeable improvement especially during low stage periods, as well as over the near-shore terminal segments of ocean tracks. We also developed other techniques, the first one based on a new waveform analytical model and the 2nd one based on the waveform deconvolution. Those 2 methods have a higher ability to fit the varying waveforms shapes over inland water. These retrackings showed high improvements on the height estimation errors.

Regarding the simulation activities, we developed new realistic simulators that are capable of providing simulated altimeter signals over those targets. To this end, the altimeter configuration (including orbit, antenna and altimeter characteristics) is used along with a surface and electromagnetic properties. Over land areas, we introduced height and slope information from a DEM model and land properties through a Land Cover mask allowing a better description of the surface roughness involved in the electromagnetic interaction of the altimeter signal. The simulated waveforms have been compared to real waveforms over several areas.

Very recent investigations of Jason-2 Ku and C-band waveforms also showed a particular alteration of the leading edges over large fresh water frozen lakes in the northern Canada. The observed signals suggest in fact that 2 distinct echoes are superimposed in each individual waveform, i.e. that the signal reflects on 2 different interfaces. The time-delay between the 2 leading edges increases regularly during the winter and decreases during the late spring. Once the time shift is converted into distance, it can be explained by the penetration into a 2-m depth or more media and a reflection at its basis. This thickness is not compatible with a snow-only layer (usually 50cm depth over these lakes): therefore, the hypothesis of a penetration up to the basis of the ice layer (2m or more...) is made.

Monitoring River Water levels from Space: Quality Assessment of 20 years of Satellite Altimetry Data

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Exploring the potential of radar altimetry for the monitoring of inland waters has been a continuous challenge since the launch of Topex/Poseidon in 1992. From inland seas to large lakes and rivers the technique was proved to provide valuable information on water level dynamics with a significant potential for improvement, as satellites were primarily designed to monitor ocean water surfaces and thus far from optimized for inland waters. Research efforts to develop the potential of radar altimetry over inland waters addressed three main directions: (1) improve accuracy and reprocess water level measurement (through appropriate retracking algorithms and better atmospheric corrections) ; (2) develop hydrological applications (river levelling, water storage estimate, flood tracking and river modelling) ; (3) contribute to the design of new satellite missions better fitted to hydrology requirements.

Efforts in these three main research directions have a common requirement: the need for a standardized approach to assess water level measurement quality, which means on one hand to quantify radar altimetry measurement accuracy through comparison with reference in situ measurement, and on the other hand to estimate radar altimetry measurement uncertainty. Providing uncertainty estimates associated to radar altimetry data over inland waters, which is not currently done, would bring a key information for hydrological applications.

To address this issue, a standard method has been developed to assess the products quality (vertical accuracy and temporal sampling loss rate (TSLR) of the satellite time series) and estimate individual measurements uncertainty. It relies on statistical characterisation of the deviation between radar altimetry measurements and in situ measured or reconstructed (from neighbour gauging stations) water levels under satellite tracks. The method is regularly applied to existing data bases (CTOH/HydroWeb, River & Lake), new products (AVISO Jason-2 GDR) and experimental products (PISTACH/Hydro), and has been implemented in the frame of a technical study to assess the performances of new retracking algorithms. It has brought a significant contribution in the field of calibration and validation of satellite hydrology and has illustrated the improvement made on the products quality.

As a global picture of the two latest decades progress made over the Amazon river network, the mean products RMS and TSLR that were respectively 1.35m and 47% for T/P (AVISO MGDR, 1992-2002) have been reduced to 0.73m and 4.5% for Jason-2 (PISTACH, 2008-2010). The quality assessment method, the current status of radar altimetry quality over rivers and its evolution over the last 20 years, through various generations of satellites (T/P, ERS-2, ENVISAT, Jason-2, CryoSat), sensors and retracking algorithms, will be presented. The elaboration of multi-satellite river water level time series over 20 years, with their associated uncertainty will be illustrated.

Direct Comparison of Absolute Water Surface Elevations Between a Global River Model and Satellite Altimeter

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Water level dynamics in continental-scale rivers is an important factor for surface water studies and flood hazard management. However, most continental-scale river models have not focused on the prediction of water level because the storage and movement of surface waters are regulated by smaller scale topography than their grid resolutions. Especially, it is more difficult to predict "water surface elevation" (i.e. absolute height of water surface from ocean surface) compared to relative water level change (i.e. water depth change within a grid-box). Here we evaluated the predictability of water surface elevation by a state-of-the-art global river model, CaMa-Flood, with sub-grid representation of floodplain topography. As a case study, the hydrodynamic simulation in the Amazon River was accomplished, and the simulated water surface elevations along the mainstem were directly compared against the Envisat altimetry. The seasonal cycle of the simulated water surface elevations well agreed to the altimetry (correlation coefficient >0.69, annual amplitude error <1.6 m) indicating that the predictability of relative water level change is high. The predictability of water surface elevations was also good (averaged RMSE of 1.83 m), and the predicted errors were within the range of the model uncertainty due to channel cross-section parameters. The direct comparison of water surface elevations between model and observation brings various information (e.g. the mean water level and the variation from it, water surface slope) which cannot be derived from the comparison of relative water level change. The comparison of water surface elevations between the model and the altimetry was restricted to the mainstem of the Amazon in this study. This limitation will be overcome by the future NASA/CNES satellite mission SWOT (Surface Water and Ocean Topography) which brings a wide swath altimeter for measuring water surface elevations. The future integration between global river models and SWOT global measurement has the potential to increase our understanding and predictive skill of the detailed process of surface water storage and transport in the world major rivers.

Global Monitoring of Large Reservoir Storage from Satellite Remote Sensing

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We studied 34 global reservoirs for which good quality surface elevation data could be obtained from a combination of five satellite altimeters for the period 1992 to 2010. For each of these reservoirs, we used an unsupervised classification approach using the Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day 250 m vegetation product to estimate the surface water area of each of the reservoirs over the MODIS period of record (2000 to 2010). We then derived elevation-area relationships for each of the reservoirs by combining the MODIS-based estimates with satellite altimeter-based estimates of reservoir water elevations. Through a combination of direct observations of elevation and surface area along with documented reservoir configurations at capacity, we estimated storage time histories for each reservoir from 1992 to 2010. We evaluated these satellite-based data products in comparison with gage observations for the five largest reservoirs in the United States (Lakes Mead, Powell, Sakakawea, Oahe, and Fort Peck Reservoir). The storage estimates were highly correlated with observations (0.92 to 0.99), with values for the Normalized Root Mean Square Error (NRMSE) ranging from 3% to 15%. The mean storage uncertainty (expressed as a percentage of reservoir capacity) for the reservoirs in this study was 4%. The multidecadal reconstructed reservoir storage variations are in accord with known droughts and high flow periods on each of the five continents represented in the data set.

Transforming Surface Water Hydrology Through SWOT Altimetry

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Significant progress has been made on the Surface Water and Ocean Topography mission since the 15yr meeting (SWOT http://swot.jpl.nasa.gov). SWOT involves NASA, CNES, and the

CSA all working intensely toward success. SWOT will measure water surface elevations across rivers, lakes, wetlands, and reservoirs with a 140km wide swath using decimeter-scale pixels having centimetric-scale height accuracies. Like the OST established by T/P, SWOT will provide a fundamentally new measurement for hydrology. Nothing like this "water surface topography" has been collected on a consistent basis from any method be it in-situ, airborne, or satellite based. Thus, SWOT will provide a transformative measurement for hydrology. SWOT data products include global water areas, estimates of river discharge, and changes in stored water volumes. Storage change measurements from SWOT are expected to have an error of 10% or better for 250m2 and larger water bodies. Storage change measurements from one-hectare water bodies are expected to have errors of 20% or better. Discharge will be estimated from algorithms with a range of complexity. Instantaneous discharge is estimated from the single instance of orbital swath data that covers a given reach. Data assimilation methods use multiple swaths from a series of repeat cycles, thus covering an entire basin and allowing a mapping of upstream flows coalescing into downstream discharge. All of these methods use SWOT measurements to estimate channel bathymetry. Discharge errors are ~10% for two studies on the Ohio River yet no in-situ data are needed to achieve this accuracy. A key to this success is that the swath provides a mapping of channel widths. Because width, depth, and water slope vary to maintain a constant discharge within a given reach, SWOT measurements of width and slope can be used to estimate unknown bathymetry. Collectively, these measurements will be used to answer important hydrologic questions. For example, what is the water balance of the Congo Basin and indeed of any basin? Just a 1mm/day error in ET over the Congo translates to a 35000cms discharge error in river flow. The annually averaged flow of the Congo River is similar to this suggested ET induced discharge error. Thus, knowing the discharge fluctuations of the Congo River and its many tributaries should improve our understanding of the water balance throughout the basin. As another example, where does a wetland receive its water: from upland runoff or from an adjacent river? Water surface elevation studies of the Amazon and Congo suggest that these two river systems differ markedly regarding water flow into and out of their respective wetlands. The implications for carbon, nutrient, and sediment fluxes are significant. There are also applications opportunities. For example, well over 100 rivers cross international boundaries, yet the sharing of water data is poor. Overcoming this via SWOT measurements should help to better manage the entire basin.

Oceanography – Mean Sea Level Trends

Regional Sea Level Variability Over The Last 60 Years From 2-D Reconstructions Based on Altimetry, OGCM Runs and Tide Gauges

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For the past decades, information about sea level is sparse and essentially based on tide gauge records along islands and continental coastlines. This dataset cannot alone inform on open ocean regional variability. But it is important to know the dominant modes of the regional sea level variability on interannual/decadal/multidecadal time scales in order to understand the physical processes which drive them. For this purpose, several two-dimensional (2-D) past sea level reconstructions over the last 5-6 decades have been developed (e.g., Chambers et al., 2002a, b, Church et al., 2004, Berge-Nguyen et al., 2008, Llovel et al., 2009, Church and White, 2011, Calafat et al. 2010, Meyssignac et al., 2011, 2012, Ray and Douglas, 2011, Hamlington et al., 2011). In this presentation we use the Empirical Orthogonal Function - EOF- approach to reconstruct past sea level. This approach uses EOFs to combine long tide gauge records of limited spatial coverage and 2-D sea level patterns based on the altimetry dataset or on runs from Ocean General Circulation Models (OGCM). We compare different past sea level reconstructions based on altimetry and OGCMs over the period 1950-2009. Their performances are discussed in comparison with independent tide gauges not used in the reconstruction process. Then, we present a 'mean' reconstruction based on an ensemble average of all individual reconstructions. In addition to this global reconstruction we propose three regional reconstructions: over the tropical Pacific, the Mediterranean sea and the Arctic Ocean. For each reconstruction, the dominant modes of temporal variability and the spatial trend patterns are discussed. Comparisons with steric sea level patterns based on in situ hydrographic data are also presented and discussed.

Twentieth-century Global-mean Sea-level Rise: is the Whole Greater than the Sum of the Parts?

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Confidence in projections of global-mean sea-level rise (GMSLR) depends on an ability to account for GMSLR during the 20th century. The known relevant effects are thermal expansion due to heat uptake by the global ocean, mass loss from the Greenland and Antarctic ice-sheets, mass loss from glaciers, and artificial changes in water storage on land due principally to groundwater mining and reservoir construction. We have made progress towards solving the "enigma" of 20th-century GMSLR:, the enigma being that the time-mean observed rate of GMLSR of about 1.8 mm/yr substantially exceeded the sum of the estimated contributions, especially for the earlier decades. On the basis of recent work by various authors we propose that: thermal expansion simulated by AOGCMs has been underestimated owing to omission of volcanic forcing in their control states; the rate of glacier mass loss was fairly constant throughout the century, probably because of the compensating effects of the warming climate and the loss of ablation area; the Greenland ice sheet could have made a positive contribution throughout the entire century due to ice discharge. Finally, we conclude that groundwater mining and reservoir impoundment may have been approximately equal and opposite. We show that it is possible to reconstruct the time series of GMSLR during the 20th century, within the uncertainties of the observational estimates, apart from a small constant residual of less than 0.2 mm/yr, which could be a long-term contribution from the Antarctic ice-sheet.

Quantifying Geophysical Causes of Global Sea-Level Rise

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Quantifying, understanding and predicting the rate of global sea-level rise remain a challenge, because the signal reflects complex interactions and feedbacks among the solid Earth, atmospheric, oceanic, hydrologic and cryospheric processes. The advent of satellite altimetry provides a unique opportunity to accurately observe the terrestrial scale and small signal of sea level rise on order of several mm/yr. The contemporary sea-level budget, that is, the discrepancy between the observation and the known geophysical causes of sea-level rise, arguably remains large, notably in the large uncertainty of our knowledge for the contributions from ice-reservoir, ice-sheet and mountain glaciers/ice caps, to the global sea-level rise. Here we use multi-mission satellite radar altimetry measurements (~20 year data span), GRACE gravimetry (~decadal data span), hydrographic data (XBT/MBT/Argo, ~5 decade data span), and tide gauge data (60iV200 year data spans), to quantify the major contributors of the 20th century and the present-day sea-level rise. Here we assume that the present-day sea level change geographic patterns as a result of various geophysical sources are known but not their respective amplitudes. The geophysical sources include the effect of elastic loading resulting from Antarctic and Greenland ice-sheets and mountain glacier melt/accumulation, thermosteric variations, solid Earth including seafloor deformation resulting from Pleistocene glacial isosatic adjustment, and hydrologic variations. First, we demonstrate the methodology using satellite altimetry and GRACE to provide estimates for each of the selected geophysical sources over the satellite data span. Finally, we add long-term tide gauge data to the suite of satellite measurements to provide an estimate of the respective contributions of the geophysical sources to the 20th century and present-day sea-level rise.

Regional Sea-level Trends from Nearly 20 Years of Radar Altimetry

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Regional sea-level trends are estimated from nearly 20 years of radar altimetry observations. Trends are estimated by taking into account the serial dependence of the data in order to obtain realistic values of the uncertainty. Furthermore, a stationarity test is applied to assess the plausibility of the linear assumption itself. The results show that most sea-level slopes are positive, indicating a general increase in sea-level at the global scale, but that the pattern of regional trends is spatially complex. Trends are not statistically significant in the eastern and central Pacific ocean and in the regions of the main current systems. Furthermore in areas of high inter-decadal variability, as in the western Pacific, sea-level long-

term variability cannot be characterized by a linear trend. The present study shows that in these regions the combination of high inter-decadal variability with the still short length of the altimetric records produces spurious trends, despite large and statistically significant slopes. It is therefore of paramount importance for the quantification of regional sea-level trends to maintain the continuous operation of satellite altimeters in order to keep and extend the current altimetric record.

An Integrated Approach to Reconstructing Sea Level

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Forming a sea level record that has the quality and duration necessary to compare past to present sea level is a challenge because of the limited spatial and temporal sampling, respectively, of tide gauge and satellite altimeter data records. To overcome these difficulties, combining the shorter but essentially complete global coverage offered by satellite altimetry with the longer but sparsely distributed tide gauge dataset is an active research area. Several studies have been published using a wide range of data and methods to reconstruct sea level back to 1950 and beyond. The number and quality of tide gauges that are available for analysis, however, limit every attempt at reconstructing sea level. In particular, prior to 1950, the distribution of tide gauges is very sparse, thus making studies on global scales difficult and studies on regional scales unfeasible. Previous sea level reconstructions back to the turn of the 19th century have focused predominantly on global mean sea level, with little discussion on the reconstruction of specific climate signals or even regional trends.

Here, we present a new method for reconstructing sea level involving cyclostationary empirical orthogonal functions (CSEOFs). While we show results from a CSEOF reconstruction using basis functions computed from satellite altimetry and subsequently fit to tide gauge data, our focus is on how other ocean observations such as sea surface temperature can be leveraged to create an improved reconstructed sea level dataset spanning the time period from 1900 to present. Basis functions are computed using satellite measurements of sea surface temperature, and using a simple regression technique, these basis functions are transformed to represent a similar temporal evolution to corresponding satellite altimeter-derived sea level basis functions. The resulting sea level and sea surface temperature basis functions are fit to tide gauge data and historical sea surface temperature data, respectively, to produce a reconstructed sea level dataset spanning the period from 1900 to present. We demonstrate the use of this reconstructed dataset for climate monitoring, focusing primarily on climate signals in the Pacific Ocean. The CSEOF reconstruction technique can be used to create indices computed solely from sea level measurements for monitoring signals such as the eastern-Pacific (EP) ENSO, central-Pacific (CP) ENSO and Pacific Decadal Oscillation (PDO). While the EP ENSO, CP ENSO and PDO are all well represented in the CSEOF reconstruction relying solely on sea level measurements from 1950 to present, we show that significant improvement can be made in the first half of the 20th century by including sea surface temperature measurements in the reconstruction.

Outreach

Chairman Introduction with BRAT

Rosmorduc, Vinca
CLS, FRANCE

Chairman Introduction with BRAT

Australia's 'OceanCurrent' Website - an Outreach Activity of the Integrated Marine Observing System

Griffin, David; Cahill, Madeleine; King, Edward; Mansbridge, Jim
CSIRO, AUSTRALIA

The 'OceanCurrent' website (http://imos.aodn.org.au/oceancurrent/) is an important component of Australia's Integrated Marine Observing System. It serves a number of functions including outreach to the general public. Altimetry, sea surface temperature and ocean colour provide contextual information to more detailed views of ocean conditions provided by HF radars and point data from Argo profilers, gliders and moorings. The 'quick look' graphics and animations complement the user-defined presentations provided by the IMOS Data Portal. OceanCurrent (as the name suggests) focusses on the current state of the ocean currents, and occasional News Items discuss the causes of interesting events such as large anomalies of sea level, temperature or current velocity, particularly those that impact large numbers of people, or major industries.

Ten Years of Progress in Downstream Oceanographic Services based on Altimetry and Other EO Data

Baudel, Sophie; Lefèvre, Fabien
CLS, FRANCE

Progress made in Earth Observation (EO) both in data quality, and operationality (daily updating, routinely supply) have made possible the development of operational downstream services for industrial customers with high level of requirements.

CLS is actively involved in the development of EO based maritime services: for about 10 years, maritime services have been developed and commercialized, targeting both industrial and institutional customers in various economic sectors, such as:

- ☐ Offshore Oil and gas companies,
- ☐ Maritime freight,

- ☐ Fishing industry,
- ☐ Institutional agencies in charge of maritime environment monitoring and forecasting (e.g. oil spills), fishing resources protection (e.g. stock estimation, quotas definition), and security (e.g. search and rescue operations)

These services are all massively based on Earth Observation satellite data, mainly altimetry sea level, altimetry geostrophic current, sea surface temperature, ocean colour, combined with advanced ocean circulation modeling and forecasting techniques data, mainly current velocity, at a global or at a regional scale. These services are now provided in near real time and have been shown to be extremely valuable for different industrial applications at sea.

Some case studies of operational services dedicated to industrial applications that have been developed and operated at CLS will be presented during our talk. Two examples are given below.

An operational service dedicated to the offshore oil and gas industry will be presented. New needs are emerging with the use of Floating Production, Storage and Offloading units (FPSO) as the distance from the coast and the depth are increasing. A precise knowledge of the open ocean conditions, both in surface and deeply is needed. Several offshore activities are concerned from the design of the structure (metocean extreme statistical criteria) to the metocean conditions forecasting delivery during a drilling or transportation operation. The commercial portfolio is covering a broad range of products and services from the delivery of high resolution surface current data forecasting to the monitoring of an oil spill with Synthetic Aperture Radar (SAR) imagery and Argos buoys. An oil spill drift prediction model assimilating SAR and buoys trajectory data is integrated in this offer. An encapsulation through a Geo Information Visualization System is proposed. Regional configuration of the service is needed and has been deployed in several offshore oil and gas strategic areas such as Gulf of Guinea, Indonesian Seas area, and the Pre-Salt offshore Brazil area.

An operational service dedicated to the maritime freight company based on mesoscale surface current prediction will also be presented. This service is based on the concept that the ocean surface currents can be used for a route "micro-optimization" for time and fuel saving.

Sea Level Education for Underrepresented Students through Collaboration with CABPES

Hamlington, Benjamin; Leben, Robert
University of Colorado at Boulder, UNITED STATES

The Colorado Association of Black Professional Engineers and Scientists (CABPES) is a non-profit organization dedicated to encouraging African-American and underrepresented youth to pursue careers in the engineering and applied science professions. The goal is to increase the number of minority scientific and technical professionals to a level that better represents the minority population, while assisting in meeting the growing demand for engineers and scientists. CABPES works primarily with underrepresented students from grades 6 through 12 and offers assistance with schoolwork as well as counseling for students preparing for college. Professional engineers and scientists volunteer their time and effort to provide this help to students.

While CABPES offers several after-school courses focusing on engineering and math, there is considerable interest in educating and informing students about the growing field of climate science. CABPES, however, lacks the resources and advisors capable of teaching students climate science. To meet this interest and to fill a gap in their curriculum, we are providing resources and materials to the students and instructors at CABPES that will increase their interest in research and scientific activities, develop their knowledge of climate science (specifically sea level change and variability), and provide them with research and hands-on experience that will aid them in future scientific endeavors. The main thrust of this project involves providing 8-week courses on climate change and sea level change twice yearly to CABPES students. With the first of these courses nearing completion, we provide an update on the success of the project to this point and highlight some of the difficulties encountered in relating the science of sea level change to the students at CABPES. We discuss the curriculum of the course that has been created and the activities that are used to help the students better understand climate science. By considering the early success and failures of the project, we provide some recommendations on ways to better communicate the subject of sea level change to high school students. The future of the project is also outlined, including the development of teaching modules that will hopefully be used in the future for dissemination to a wider audience than just the students at CABPES.

Education, Outreach, and Societal Benefits of Ocean Altimetry Missions: 20 Years of Communication & Collaboration

Srinivasan, Margaret; Richardson, Annie
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A nearly 20-year record of ocean surface topography (OST) measurements has resulted in benefits not only to altimetry science team members, but also to the broader scientific and education communities, and to society as a whole. The outreach and applications efforts, which came into being with TOPEX/Poseidon and have continued with the Jason missions, has focused throughout, on the importance of making the knowledge gained from the missions available to the general public, using tools and media that are audience appropriate.

The goals of our team continue to include:

- ☐ Increasing awareness of ocean altimetry missions
- ☐ Featuring operational and research applications (both altimeter and multi-sensor)
- ☐ Promoting the societal benefits of altimetry data and science results
- ☐ Providing oceanography content for educational uses
- ☐ Inspiring the next generation of scientists and engineers

It is increasingly relevant to promote the use of mission data and results for science and societal benefits as well as for education purposes, which support the teaching of science, technology, engineering and math (STEM) subjects in schools. Reaching our target audience members in the education, general public, and current or potential operational/commercial data users, has been primarily achieved through web interfaces, printed products, and media stories addressing scientific results, education, OSTST member activities, and mission milestones. An underlying message for all communities is the direct societal benefits gained from ocean altimetry measurements. As we review our past efforts, focus on current datasets and results, and look toward future missions and new discoveries, we continue to seek support and interactions with OSTST members as partners in our outreach and applications efforts. We recognize this partnership as key to a successful ocean altimetry outreach program, which keeps the public fully informed and involved in our missions and scientific breakthroughs in the upcoming decades.

Altimetry on the web: Aviso

Rosmorduc, Vinca[1]; Bronner, Emilie[2]; Maheu, Caroline[1]
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If the altimetry continuous series of data date from 1991-1992, altimetry web sites are a little younger: Aviso Altimetry web site dates from 1996. At the beginning, the Aviso web site was mostly made to publish data "status". It quite quickly included some applications & sciences topics (mostly leaflets transposed on line), and the Aviso Newsletters in a second stage. The biggest evolution occurred in 1998, with a much more complex and complete web, with full section about applications, regular updates, etc. The Aviso web site is now at its fourth version, and continues to evolve every day! We will detail the history of the different version and their aims, but also (mostly) the audience and its evolution, the impact of the editorial line and of the update scheme. See www.aviso.oceanobs.com

Hydrology and Land Processes II

A Comparison of Water Storage Change from Satellite Altimetry and GRACE over the Great Bear Lake, Canada, and Bratsk Reservoir, Siberia.

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Satellite altimetric measurements over lakes and reservoirs provide the water level variation which when combined with the areal extent give a time series of water storage change. In this study we consider the Great Bear Lake and the Bratsk Reservoir, Siberia. The latter, with area of 5,470 square kilometres and volume of 169.27 x 1012 litres, is one of the largest artificial lakes in the world. For major lakes the change in water storage has the potential to provide a gravitational signal that can be observed by the GRACE gravity field mission. In this study we utilise ENVISAT altimetry both directly from the GDRs and from retracking to provide a measure of the water storage change with the altimetric heights compared against gauge data. The water storage change is subsequently converted to a surface mass change to simulate the gravitational signal sensed by the GRACE gravitational field mission. We then compare this simulated signal with the actual gravitational signal estimated from the GRACE data.

Satellite-based Estimates of Surface and Groundwater Storage Variations in the Amazon Basin

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Spatiotemporal variations of surface waters can be determined by combining observations from satellite imagery and radar altimetry. In this study, we use (i) a multisatellite monthly inundation product available globally with a spatial resolution of 25 km, and (ii) water levels derived from ENVISAT RA-2 altimetry data over more than 600 locations in the Amazon Basin during the period 2002-2007. Water stored in the aquifer is isolated from the total water storage measured by GRACE by removing the contributions of both the surface reservoir, derived from satellite imagery and radar altimetry, and the root zone reservoir simulated by hydrological models such as LaD and WGHM. The spatio-temporal variations of surface and groundwater reservoirs are compared to other hydrological datasets (i.e., rainfall from TRMM or GPCP, discharges, ...) and analyzed at sub-basin scale in the context of the climate variability and recent extreme events such as the drought of 2005. These results are also of great interest for the preparation of the future wide swath altimetry mission SWOT (Surface Water and Ocean Topography) that will measure 2D water levels over a 120km swath.

Flood Mapping Inferred from Remote Sensing Data

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In ungauged basin, space-based information is essential for the monitoring of hydrological water cycle, in particular in regions undergoing large flood events where satellite data may be used as input to hydrodynamic models. A method for near 3D flood monitoring has been developed which uses synergies between radar altimetry and high temporal resolution multi-spectral satellite. Surface Reflectance from the MODIS Terra instrument are used to map areas of open water as well as aquatic vegetation on a weekly basis, while water level variations in the inundated areas are provided by the radar altimetry from the Topex / Poseidon (T/P), Jason-2 and Envisat satellites. We present this synergistic approach to three different regions: Niger Inner delta in Africa, Andean Altiplano in South America and Ganga river delta in Asia. Based mainly on visible and Near Infra Red (NIR) imagery is suitable to the observation of inundation extent. This method is well adapted for arid and semi arid regions, but less for equatorial or boreal ones due to cloud coverage.

This work emphasizes the limitations of current remote sensing techniques for full 3D-description of water storage variability in ungauged basins, and provides a good introduction to the need and the potential use of the future SWOT (Surface Water and Ocean Topography) satellite mission.

Flood Monitoring From Space

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Floods are the leading cause of natural disaster losses in the world, and economic losses have continued to rise with increased urbanization in flood-hazard areas. The 2004 UNESCO World Disasters Report estimated that flooding affected 116 million people globally, causing 7000 deaths and leading to $7.5 billion in losses. Flood is also the most frequently occurring disaster type among all other natural disasters such as earthquakes, volcanoes, wind storms, wild fires, tsunami, slides, extreme temperature, and epidemics around the world. Hence, timely monitoring of changing of river, wetland and lake/reservoir levels is important to support flood disaster monitoring and proper response. The future wide-swath interferometric altimetry, NASA's/CNES' Surface Water and Ocean Topography (SWOT) mission, to be launched in 2019, is anticipated to revolutionize hydrologic surface water science from space, and would have the required spatial resolution and temporal sampling to measure the extent and intensity of floods, potentially in a timely fashion. While SAR/InSAR technology at present suffers latency problems, satellite radar altimetry is on the verge of being able to provide near-real time data for flood monitoring. Here we present the feasibility of extending the capability of contemporary radar altimeters (18-Hz Envisat, 20-Hz Jason-2, the planned 40-Hz AltiKa, and the CryoSat-2 SIRAL data) for potential near-real time surface flood monitoring. Here we study several proof-of-concept cases for timely monitoring of recent flood episodes, flood heights and extents using altimetry and other data sets (MODIS, GRACE), including 1997 Red River floods, the 2009 Amazon record flood on Rio Negro, the 2010 floods in Pakistan and China, the 2011 Australian, Memphis and Thailand floods. We also provide a projection of how SWOT would significantly improve the temporal and spatial resolution of future flood monitoring.

Downscaling of Flooded Fraction Derived from Low-Resolution Multi-Satellite Measurements in Preparation for the SWOT Mission

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A climatology of wetlands has been derived at a low spatial resolution (0.25°x0.25° equal-area grid) over 15 years by combining satellite observations in the visible, near-infrared and passive and active microwave (Prigent et al., 2001, 2007; Papa et al., 2010). The objective of this study is to develop innovative downscaling techniques able to retrieve wetland estimations at a high spatial resolution (~100 m). Two different approaches are tested.

The first technique uses an image processing approach and information on the low and high wetland season. This method is tested over the densely vegetated basin of the Amazon with SAR data (Hess et al., 2003).

The second technique uses a statistical decomposition of the space/time variability of the wetland area based on regular high spatial resolution visible observations. This second method is tested over the semi-arid region of the Niger delta using MODIS data (Berge-Nguyen et al., 2008).

This new downscaled high spatial resolution information on the wetland dynamics will be compatible with the SWOT spatial resolution. As a consequence, our high-resolution climatology will allow the analysis of the SWOT mission and the optimization of its instrumental characteristics. The new high-resolution wetland climatology will also help define the Cal/Val sites.

Oceanography – Integrated Systems – Applications – Forecast – Assimilation I

Observations of the Influence of Eddy-induced Ekman Pumping on Phytoplankton Trapped in Nonlinear Anticyclonic Mesoscale Eddies

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High-resolution sea-surface height (SSH) fields constructed from altimeter data have revealed the ubiquity of nonlinear, coherent structures ("eddies") with mesoscale radii of ~100 km throughout the World Ocean. We investigate the influence of these eddies on oceanic biology from 10 years of upper-ocean chlorophyll estimates derived from satellite measurements ocean color collocated to the eddies inferred from the SSH fields. At temporal scales of weeks to months and spatial scales greater than about 100 km, the dominant mechanism for chlorophyll variability is shown to be eddy-induced horizontal stirring of the ambient chlorophyll field. The resulting dipole structure of chlorophyll within the eddy interiors depends on the direction of eddy rotation and the direction of the background large-scale gradient of chlorophyll.

While horizontal advection by the rotational velocities of the eddies dominates the statistics of chlorophyll variability globally, trapping of chlorophyll within the cores of eddies is found to be important in anticyclonic eddies in regions where the chlorophyll concentration is high within the eddy interiors at the time of formation. The active biology required to sustain these phytoplankton populations involves complex ecosystem dynamics that vary in both space and time. From collocation of scatterometer wind fields to the eddy interiors as inferred from the SSH fields, it is shown that the interaction between the anticyclonic eddy surface velocity and the larger scale background wind field results in sustained cyclonic wind stress curl localized over the anticyclones. This eddy-induced Ekman pumping, which can exceed 1 m day^{-1}, injects nutrients into the euphotic zone and thus plays a critically important role in sustaining the ecosystems that are trapped within the nonlinear cores of the anticyclonic eddies.

The influence of eddy-induced Ekman pumping on marine phytoplankton is clearest in the South Indian Ocean, where the chlorophyll response varies seasonally with the largest blooms occurring during the winter. Argo float profiles of temperature and salinity are collocated to the eddy interiors to investigate the seasonal variability of the vertical structures of the anticyclonic eddies. It is shown that the ecosystems trapped within the interiors of eddies respond to eddy-induced Ekman pumping only when the mixed layer is deeper within the eddy interiors compared with outside of eddies. This synergistic collocation of satellite data (SSH from altimetry, chlorophyll from ocean color, wind stress from scatterometry and vertical structure from Argo profiles) provides new insight into biophysical interaction within anticyclonic nonlinear mesoscale eddies.

Guiding Biogeochemical Campaigns with High Resolution Altimetry: Waiting for the SWOT Mission

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Biogeochemical processes in the ocean are strongly affected by the horizontal mesoscale (~10-100 km) and submesoscale (1-10 km) circulation. Eddies and filaments can create strong dishomogeneity, either amplifying small-scale diffusion processes (mixing) or creating tracer reservoirs. This variability has a direct effect on the biogeochemical budgets - controlling for instances tracer fluxes across climatological fronts, or part of the vertical exchanges. This variability also provides a challenge to in situ studies, because sites few tens of kms or few weeks apart may be representative of very different situations. Here I will discuss how altimetry observation can be merged with other satellite data in order to track in near-real-time transport barriers and mixing regions and guide a biogeochemical adaptative sampling strategy. In particular, I will focus on the recent KEOPS2 campaign (Kerguelen region, October-November 2012) which employed Lagrangian diagnostics of a specifically designed high resolution, regional altimetric product produced by CLS (with support from CNES). The integration of such product with Lagrangian diagnostics, drifters, CTD casts, and other satellite data allowed to sample the evolution of the bloom over several contrasted sub-regions of the Kerguelen area, providing a detailed picture of its biophysical dynamics for more than one month. Such approach opens to way to the exploitation of incoming high resolution altimetry data expected from SWOT for biogeochemical studies.

Evaluation of the Latitudinal Variations of the Southern Ocean Sea Water pCO2 in CMIP5 ESMs using Shipboard Measurements and Satellite-derived Ocean Currents

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Southern Ocean uptake of anthropogenic CO2 from the atmosphere is essential to the atmospheric CO2 projections in

CMIP5 Earth System Models (ESMs). Fluxes of CO2 into the ocean are determined by the differences in the partial pressure of CO2 (pCO2) between the surface ocean and the overlying atmosphere. Recent measurements have found that pCO2 in the surface waters of the Southern Ocean has increased at a rate that is similar to or slightly faster than the mean atmospheric rate of increase. Warming of the upper 1000 m of the Antarctic Circumpolar Current (ACC) system might play a role in the increased Southern Ocean pCO2 values. Increased upwelling south of the ACC fronts driven by the strong, poleward shift of the westerly winds further brings rich Dissolved Inorganic Carbon (DIC) from the deep ocean to the surface, but this may be offset by the reduced area (poleward shift of ACC fronts) over which upwelling occurs. The cross-frontal pCO2 transport redistributes the pCO2 in the surface Southern Ocean. To understand the interplay of these physical processes, we intercompare the latitudinal variations of the sea water pCO2 in the Drake Passage in CMIP5 ESMs. The underway decade-long (2002-2012) shipboard pCO2 measurements across the Drake Passage, the scatterometer winds, and the altimetry-derived ocean currents serve as an important benchmark for evaluating the CMIP5 ESMs during that time period. Shipboard measurements show that sea water pCO2 is in equilibrium with the atmosphere near the ACC fronts and is unsaturated away from the fronts. CanESM2 (Canada) and other three ESMS from Germany, China, and Japan generally resemble the observed pCO2 variations, while INMCM4 (Russia) changes little with latitudes. The seasonal amplitude of the observed pCO2 north of the fronts is triple the amplitude south, while the seasonal amplitude of the CanESM2 pCO2 is much larger than the observations. The air-sea CO2 flux in CanESM2 reaches maxima near the fronts, where the ocean nearly equilibrates with the atmosphere. The possible reason is that the erroneously intensified westerly winds simulated in some ESMs transport rich upwelled DIC out of the Drake Passage, causing a deficit of CO2 near the fronts, and the ocean acts to take up extra CO2 to equilibrate with the overlying atmosphere. The role of the strong stratification north of the fronts in prohibiting the CO2 from downwelling to the deep ocean is also addressed.

The Contribution of Satellite Altimetry and Ocean Models to Ecosystem-based Fishery Management

Gaspar, Philippe; Lehodey, Patrick; Senina, Inna
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Marine ecosystems provide an important share of the food and resources of the World's population but many fish populations are overexploited and the ecosystems in which they live are degraded. As a consequence, there is now a strong institutional demand to develop ecosystem-based fishery management (EBFM). The objective of EBFM is to obtain and maintain long-term socio-economic benefits from a fishery, without compromising the ecosystem that sustains it. EBFM also aims at generating knowledge of the ecosystem functioning, sufficient to understand the likely consequences of human activities. Where knowledge is insufficient, precautionary fishery management procedures, systematically favoring the ecosystem, must be used.

In this paper we will show how satellite altimeter measurements, jointly used with coupled ocean and fish population dynamics models, contribute to the understanding, and hence the proper management, of marine ecosystems. We will focus on pelagic ecosystems, the tuna fishing industry and its interactions with protected species such as sea turtles.

Satellite data and operational ocean models now provide the necessary inputs for models of the lower to mid- and upper trophic levels of marine ecosystems. SEAPODYM is such an end-to-end model simulating the evolution of tuna populations and their prey under the combined pressure of climate change and fisheries. To this aim, fish catches are imposed in the model using actual catch reports or estimations of the fishing effort. The environmental forcing is provided by operational ocean models, such as those developed in the European ocean monitoring and forecasting project MyOcean. SEAPODYM is currently used to support tuna stock assessments, help define Marine Protected Areas, or establish the likely impact of climate change on the long-term evolution of tuna populations.

SEAPODYM will be rapidly presented here and, through a few examples, we will show that:

- ☐ Assimilation of satellite altimetry data into ocean models are indispensable to provide realistic high-resolution forcing to fish population dynamics thereby allowing proper simulations of the mesoscale variability of tuna catches and thus more detailed and accurate regional stock assessments
- ☐ Satellite altimetry data combined with ocean models and satellite-tracking of marine animals can be used to better define habitats of endangered sea turtle species and then inform fishermen about areas where fishing should be avoided to minimize incidental catches.

CryoSat-2 Mission: A Contribution to the Operational Altimetry Constellation for the Mesoscale Observation

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Cryosat-2 is ESA's ice mission which primary objective is to serve Cryosphere science. Nevertheless, Cryosat-2 has, in theory, the potential to be a mission of opportunity for oceanography. Indeed, the satellite embarks an innovative radar altimeter, and high-precision orbit determination (POD), which are expected to be at least as accurate as ENVISAT's.

Despite the differences between the design of Cryosat-2 and other radar altimetry missions, Dibarboure et al. (2011)

showed through an end-to-end experiment that Cryosat-2 had the potential to bring a significant contribution to mesoscale observation. If ocean data from Cryosat-2 are processed and cross-calibrated with Jason-2, it is possible to merge Cryosat-2 measurements with other radar altimeters to improve the resolution of multi-satellite mesoscale fields, especially in regions of high variability such as the Gulf Stream.

Thanks to joint effort between CNES and ESA space agencies, the Cryosat-2 mission was integrated into the Near Real Time altimetry multi mission centre SSALTO/DUACS. Since early days of 2012, operational multi mission SLA products (Level 3 along track and L4 maps) are routinely available on AVISO and MyOcean catalogues.

In addition to the scientific achievements, the integration of Cryosat-2 in the operational altimetry constellation as a mission of opportunity helps to mitigate the upcoming loss of ageing altimetry satellites (Jason-1, ENVISAT).

The Cryosat-2 altimeter is operated almost continuously over ocean, either in Low Resolution Mode (like conventional pulse-limited altimetry sensors) or in the so-called Doppler/SAR mode (higher-resolution and lower noise level). While the optimised SAR processing are not yet available, CNES has developed a pseudo LRM processing that allows recovering data in all the SAR and SARin acquisition regions. Even if the noise is higher than the traditional LRM mode, this is a major achievement that provides a global continuous coverage, especially for Europeans seas such as North Atlantic Ocean, Mediterranean Sea and Black Sea.

This paper addresses several examples of the improvements coming from Cryosat-2 mission for the mesoscale observation system, especially at high latitudes which were previously covered only by ENVISAT.

Monitoring the Ocean from Observations

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Producing comprehensive information about the ocean has become a top priority to monitor and predict the ocean and climate change. Complementary to modeling/assimilation approaches, an observation-based approach is proposed here. It relies on the combination of remote-sensing (altimetry and sea surface temperature) and in-situ (temperature and salinity profiles) observations through statistical methods.

The method uses first a multiple linear regression method to derive synthetic T/S profiles from the satellite measurements. These synthetic profiles are then combined with all available in situ T/S profiles using an optimal interpolation method. The thermal wind equation with a reference level at the surface is finally used to combine current fields from satellite altimetry with the thermohaline fields to generate the global 3D geostrophic current fields. Global temperature, salinity, absolute height and geostrophic current fields are thus available at a weekly period from the surface down to 1500-meter depth and a reanalysis is available for the 1993-2010 periods. The method has been assessed through comparison with independent in situ data sets as OVIDE sections or RAPID current meter array. An analysis of the ocean variability using the 18-years long time series of the global 3D-fields of temperature, salinity and current has then been performed. The temperature variability of the 1993-2009 periods shows a clear warming that is visible at all depths and for all latitudes. If the variability is baroclinic with strong interannual signals in the tropics, it shows a clear long term trend at high latitude with depth consistent signals. Changes of ocean circulation are also been studied through mass transport at key regions and maximum Atlantic Meridional Overturning Circulation strength. Although high interannual variability is observed in the AMOC time series, it is not possible to extract a clear trend. Our analyses have also been compared to other observation-based approach (Roeammich and Gilson, 2009) and to outputs from numerical models (SODA, GLORYS).

20 Year Trends in the Surface Circulation

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OSCAR surface currents (Ocean Surface Current Analyses Real-time) are global surface currents derived from satellite-sensed sea surface height, ocean vector winds, and sea surface temperature. OSCAR currents are calculated from an analytical model based on geostrophy, Ekman, and thermal wind dynamics. Over the last 17 years, OSCAR has evolved from a tropical study of surface currents to a global surface current database provided in near real-time on a third-degree grid. Agreement with in situ data is strong, particularly in highly geostrophic regions. For example, the correlation coefficient between drifting buoys and OSCAR currents in the Gulf Stream region is consistently around r=0.9.

Here we explore the circulation patterns associated with mean sea level rise over the last two decades and the balancing, or not balancing, large-scale Ekman currents. We will contrast the trends implied by geostrophic balance based on mean sea level change with the trends in geostrophic currents observed in OSCAR. In addition, long-term trends in fast timescale dynamics, such as eddy kinetic energies, are calculated from the OSCAR timeseries.

We observe dominantly zonal signals in the 20-year geostrophic current trend. The strongest trends are observed in the tropics, with banded structures between 10 S and 20 N. The strongest Ekman current trends are also observed in the tropics, although with a different structure to the geostrophic currents and with a weaker trend. We will focus on the Tropical Pacific, analyzing the shifting of El Nino/Southern Oscillation (ENSO) dynamics over the last two decades. Surface current anomalies are highly correlated with SST anomalies and precede SST anomalies by several months, showing that surface horizontal advection plays a major role in the evolution of ENSO. This trend is consistent over 20 years of SSH and SST data. Shifts in Western Boundary Currents can also be seen in the 20-year record, reflecting the shifts in basin circulations. The circulation trends in each basin will be explored in this paper, with emphasis on the insights gained from a two decade long SSH record.

Coastal Altimetry

The PISTACH Project for Coastal and Hydrology Altimetry: 2012 Project Status and Activities

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The PISTACH project (funded by CNES as part of Jason-2 project to improve satellite radar altimetry products over coastal areas and continental waters) was initially organized around 3 phases:

- ☐ Phase 1 (Nov 2007 - March 2008): user needs and structure of coastal/hydrological products
- ☐ Phase 2 (Nov 2007 - July 2008): Development of new dedicated algorithms: retracking of the waveforms, wet and dry tropospheric corrections, local models or high resolution global models for topography, geoid, land cover classification, land water mask, data editing
- ☐ Phase 3 (July 2008 - Sept 2009): prototype implementation, validation and operations during Jason-2 CalVal phases

The input of the prototype is constituted by Jason-2 Level 2 S-IGDR altimeter products, ECMWF meteo fields, as well as several state of the art static auxiliary datasets (DEM, geoid, ...). The first version of PISTACH products adopts the same format and structure as Jason-2 standard IGDR to facilitate their appropriation and assessment by expert users.

The implementation of the prototype was completed in autumn 2008 and products in V1.0 are accessible since cycle 1 of Jason-2 at the following ftp address ftp://ftpsedr.cls.fr/pub/oceano/pistach/

After the initial 3 phases of the project, CNES decided, for the following years, to continue the operation of the PISTACH prototype together with the creation of a user's handbook and some data use cases, accessible on the AVISO web site (http://www.aviso.oceanobs.com/).

We will present the PISTACH project and its evolutions, the products, the user's handbook, and possible future activities.

COASTALT Project's Contribution to the Development and Dissemination of coastal Altimetry

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The present contribution revisits briefly the many recent technical improvements that are contributing to the steady progress of the new field of Coastal Altimetry and in particular focuses on the results of the ESA-funded COASTALT project (2008-2011), which has recently concluded.

COASTALT has been an excellent incubator of ideas and new techniques for the improvement of coastal altimetry: first of all it has contributed to establish user requirements for this new field, and it has defined detailed product specifications for the new coastal altimetry products and produced the relevant documentation. At the same time COASTALT has tackled the two main areas of improvement for coastal altimetry. These are: 1) retracking, i.e. fitting a waveform model to the waveforms to obtain an estimate of the geophysical parameters: and 2) designing and validating improved coastal corrections for the effects of the atmosphere and/or other geophysical phenomena, like tides.

The main results of COASTALT, as far as retracking is concerned, are the innovative techniques to deal with the waveforms in proximity of the coast, where there are often quasi-specular returns due to stretches of calm water which prevent a successful use of the standard (open-ocean) Brown-model retracker. This issue has been investigated in a number of cases around islands, and a hyperbolic pre-tracker has been suggested as a way to precondition the waveform stack prior to conventional retracking. We will show examples of its application.

In terms of coastal-specific corrections, the main contribution by COASTALT has been the implementation of an innovative scheme for the Wet Tropospheric Correction (i.e. the path delay due to water vapour in the troposphere) based on GPS observations and following pioneering research by the University of Porto. These concepts will be presented in some detail.

An important part of the COASTALT mission has been to facilitate the coming together of the international coastal altimetry community of researchers. This has been achieved via the moderation of the coastal altimetry forum, the direct involvement of COASTALT staff in the organization of the Coastal Altimetry Workshop, and the contribution by various COASTALT authors to the new book on "Coastal Altimetry" published in 2011.

We will conclude this talk by drawing the final recommendations by COASTALT and illustrating some of the possible scientific applications that make coastal altimetry an effort well worth the investments currently being made by ESA and by the research community, like the one to storm surge monitoring within the new eSurge project. It is fair to wrap-up by saying that with COASTALT, ESA has created an asset that firmly places ESA-funded research in this novel sector clearly at the focus of the international scene.

Effectiveness of Various Environmental Corrections and Sea Level Variability near the Indian Coast using PISTACH Coastal Product

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Coastal regions are important part of the global oceans because of several crucial aspects pertaining to science, society and economy. However, altimeter and radiometer instrument observations are perturbed near the lands, which lead to absence of data in this important part of the ocean. Distributed datasets from various agencies are mostly meant for open ocean studies. However, altimeter and radiometer do give measurements which contain useful information for areas between 50 km offshore and the coastline. CNES funded PISTACH project supported by ESA have distributed coastal and hydrology products for the expert users.

The range measurements from the altimeter are associated with a large number of geophysical corrections which needs special attention near coasts and the shallow water regions. The corrections due to ionosphere, dry and wet troposphere and that due to sea state are of primary importance in altimetry. The present study involves the comparison of the water vapor corrections estimated from radiosonde measurements near the coastal regions with the model estimated corrections applied in the altimeter range measurements. Identification of the rain events and estimation of the rain rate using altimeter backscatter measurements using differential attenuation of KU and C band for the tropical cyclones over Indian seas and their comparison with other available collocated satellites observations has also been attempted. using the Coastal Altimeter products provided by the PISTACH near the Indian coast. The PISTACH data for the Indian coastal regions of the one year period has also been used for the Sea Level Anomaly (SLA) variability study. Differential behavior of SLA variability has been observed for the eastern and the western coast of Indian landmass. Fast Fourier analysis of SLA performed at different coastal points show different periodicities. Seasonal variations of the SLA along the coast have also been studied. Detailed results will be presented in the workshop.

3D Coastal Mesoscale from lagrangian Analysis of Altimetry and Multi-Sensor Observations

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Oceanic mesoscale plays a key role in modulating large-scale circulation, heat fluxes and primary production enhancement. Such hydrodynamic processes are also crucial at regional scales where the associated currents are known to significantly influence water-mass mixing and exchanges between the coastal zone and the open ocean. Nevertheless, the characterization of coastal mesoscale dynamics from along-track altimetric observations is complicated from a technical and algorithmic point of view and thus requires continuous developments (refer to the CTOH-XTRACK processor, PISTACH and COASTALT initiatives).

Moreover, the high spatial/temporal variability and complexity associated with coastal mesoscale processes make them difficult to be studied with sparse in-situ observations and highly-smoothed standard altimetric products which lack the high resolution often required to correctly represent regional features. Alternative options rely on generating satellite altimetric maps specifically adapted to the coastal domain and also on developing methodologies based on the fusion of multi-sensor platforms in conjunction with numerical simulations. In this respect, optimal interpolation methods for improving the coastal circulation description have been developed over the North Western Mediterranean Sea (NWM), an area marked by a relatively low signal to noise ratio compared to the global ocean. We have also used vertical Empirical Orthogonal Functions (from a numerical model and in-situ measurements) in order to rebuild realistic coastal geostrophic currents both at surface and throughout the water column.

Our approach characterizes the main coastal mesoscale features which can be confirmed by comparison with several independent in-situ measurements done by the MIO and IMEDEA laboratories (drifters, ADCP, gliders...). In particular, the developed methods are able to improve the accuracy of surface geostrophic current compared to standard AVISO product. Even better results can be obtained when complementary geophysical information (from bathymetry, sea surface temperature, tide gauges) are integrated in the optimal interpolation scheme. The high resolution 3D currents were then coupled with a Lagrangian code to simulate particle trajectories and therefore better interpret the influence of coastal mesoscale circulation on 3D exchanges between the Gulf of Lion continental shelf and the NWM open sea. Finally, the long-term statistical analysis (> 10 years) of these current fields was exploited to better characterize potential inter-annual changes in the coastal mesoscale activity of the NWM.

The Source of the Leeuwin Current Seasonality

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The twenty year record of satellite altimetry is used to show that the Leeuwin Current seasonal cycle originates from an annual pulse of sea level generated in the North West Shelf that propagates around the Australian coastal waveguide. The Pacific Ocean is not the source of the annual sea level pulse. The annual Rossby wave at 5ºN does not penetrate into Indonesia possibly due to interaction with the Mindanao Eddy. The presence of an 'annual barrier' to the north of Indonesia is demonstrated in sea level, temperature and salinity observations. The monsoon forced seasonal build-up of sea level in the Gulf of Carpentaria (GOC) provides a potential source for the Leeuwin Current seasonality but little of this signal appears to leak out of the region. In fact, a region of high sea level forms locally within the North West Shelf in January which rapidly propagates southward along the western and southern Australian boundary. This sea level feature is forced by an anomalous increase in heat flux to the region which generates an observed annual increase in sea surface temperature. South of the North West Shelf, the sea level pulse appears to be forced by local winds along with its remote origins. The pulse also displays anomalous temperature and salinity signals that are modified by mixing processes along its 7000-km path-length. The change in cross-shelf sea level gradient along the western and southern boundaries drives the seasonal changes in the Leeuwin Current flow.

Using HF Radar Coastal Currents to Correct Satellite Altimetry

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A challenge of coastal ocean satellite altimetry is correcting for altimetric waveform distortions due to the presence of land within the instrument footprint. Many retracking procedures have been developed for this correction but there is great difficulty in knowing what is the proper method and where it is best applied. A possible fiducial data set is the Coastal HF radar (CODAR) network which continuously monitors surface currents hourly off the west coast of the U.S from 50 km to 150 km offshore depending on the horizontal resolution (2 km and 6 km respectively). First the time and space scales of the coastal ocean are computed using the CODAR velocities. Second, we remove shorter time scale effects of tides and wind forcing over the California Coast by averaging the CODAR over three day to get an approximation of the geostrophic currents. Third, we assume that the local current fields are isotropic and homogeneous and fit them to a stream function to retrieve their matching synthetic height fields mapped with a varying spatial scale optimal interpolation. Testing on regions more than 30 km offshore demonstrates a similarity between the CODAR derived synthetic height fields and those computed directly from satellite altimetry.

Data from satellite altimetry are degraded by the occurrence of unusually high radar return backscatter cross-section sigma0. Called sigma0 blooms they occur in regions of weak winds, and in the presence of surface slicks. These higher sigma0 values cause a breakdown in the typical Brown open-ocean waveform model. The waveforms may also be corrupted when the backscattering cross section is not uniform in the footprint of the altimeter with reflecting and localized patches. Such events occur frequently on the California coast and we are now searching for strategies to reduce the errors due to blooming events using CODAR synthetic surface heights as a reference. We use the evolution of the waveforms before and after the point of retrieval to depict the changes in sigma0 over the footprint and incorporate them in the retracking method to adjust for an inhomogeneous ocean.

We intend to improve the altimeter surface heights estimate closer to shore due to land contamination using the CODAR synthetic heights as a guideline. First we will use the 20 Hz Jason-2 PISTACH coastal product. This product gives the altimeter's range from several retrackers such as MLE4, Red3 and Ice3. Over the open ocean the 1-Hz range rate measurement is sufficient to describe mesoscale variability, but not in the coastal regions where the spatial scales decrease. The 20 Hz data, although noisy, enables us to examine the possibilities of new sampling strategies for higher altimeter resolution such as 5 Hz closer to shore. We wish to also determine which retracker better fits the CODAR synthetic heights depending on sea state. Other retrackers such as the Gaussian Peak retracker need to be implemented and validated near the coast.

An Inter-comparison Between Algorithms For Wet Path Delay Retrieval In The Coastal Regions

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In the last years, major advances have been made in the field of Coastal Altimetry, with the development of various methodologies for the computation of the wet tropospheric correction in the coastal zone. Three main approaches have been proposed for the retrieval of the wet path delay in the altimeter measurements in the coastal regions, where the Microwave Radiometer (MWR) measurements become invalid due to land contamination in the radiometer footprint:

(1) Land Contamination Algorithm (LCA);

(2) Mixed-Pixel Algorithm (MPA);

(3) GNSS-derived Path Delay (GPD) approach.

The first method, based on the correction of the MWR measured Brightness Temperatures (TBs) from the contamination by the percentage of land in the radiometer footprint, followed by a retrieval of the path delay (PD) by reapplying the same algorithm developed for open ocean, has been implemented to Jason-2 data in the scope of project PISTACH. The second approach, based on the parameterization of the algorithm coefficients as a function of the 18.7 GHz land fraction using a database of modeled coastal TBs has been developed at the Jet Propulsion Laboratory (JPL) and applied to Jason-1 and Jason-2 data. The third technique (GPD) is based on the combination of PDs derived from GNSS (Global Navigation Satellite System) with valid MWR measurements in the vicinity of the point and PDs derived from a Numerical Weather Model (NWM) such as the European Centre for Medium-range Weather Forecasts (ECMWF). GPD has been developed in the scope of ESA project COASTALT, further refined and implemented to Envisat in the scope of ESA project Sea Level CCI.

This study presents an inter-comparison of the three techniques with respect to various issues.

A summary of each technique is first presented with focus on the methodology, data requirements, accuracy and specificities of the application to each altimeter mission.

For the Jason-2 mission these methods are inter-compared and validated by performing a set of analyses such as: 1) Sea level anomalies (SLA) variance function of the distance from the coast and SLA variance at crossovers; 2) comparison with independent measurements of wet PDs such as GNSS-derived PDs (at stations not used in GPD), global and local NWM and observations from radiosondes; 3) SLA comparisons at tide gauges.

Finally, the strengths and weaknesses of each methodology are discussed, as well as the possibilities for improvement of each individual technique or through the merge of techniques.

Hydrology and Land Processes III

Radar Altimetry for Improving a Large Scale Hydrodynamic Model of the Amazon

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We present the use of radar altimetry data to improve the large-scale hydrological model MGB-IPH in the Amazon River basin. This physically-based model uses a 1D hydrodynamic module resolving the complete Saint-Venant equations and using a simple floodplain storage model. River-floodplain geometry parameters are extracted from SRTM DEM using GIS algorithms. The model was forced using satellite-derived daily rainfall TRMM 3B42, and calibrated against discharge data. We first perform a model validation using river water levels derived from ENVISAT altimetry data, but also in situ daily discharges and other remotely sensed products. Model results agreed well with observations, especially with discharge data. The model also represented inter-annual variability and hydrological extremes. Although the model provided realistic water levels in most of the validation sites, ENVISAT data shows some model limitations. Large water level biases were found in some river reaches and errors in water level amplitude in others. Uncertainty in river and floodplain geometry, estimated using geomorphological relations and the SRTM DEM, may be an important source of these errors. Finally, we present prospects on the use of radar altimetry data (i) to guide an improvement of the flood inundation representation within the model and (ii) in a data assimilation system aiming hydrological forecasts.

Satellite Monitoring, Warning/alert System, and Seasonal/Interannual Variability of the Poopo-UruUru Lake System and Coipasa and Uyuni Salars.

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The Poopo-UruUru Lake is part of a lacustrine lake-river system located within the Peru and Bolivian Altiplano. It is part of the TPDS (Titicaca - Poopo - Desaguadero - Salars) system that covers more than 190000 km2. It extends north-south over more than 1000 kilometers and is west-to-east 200 km wide (14º03' and 22º50' south latitude, 71º- 66º east longitude). During colder and/or wetter episodes in the past, this hydrologically closed basin have contained substantial lakes. Thus, some 40000 years ago, the area was part of the Lake Minchin, a geant prehistoric lake, which extended 200 km E-W and 400 km N-S, and attained a depth of 140 m. When the lake dried, it left behind the Poopo-

UruUru lake system, and two major salt deserts, salar de Coipasa and the larger Uyuni, which are respectively the fifth (2218 km2) and the world's largest salt flat (10582 km2). Interestingly, these two large salt deserts, plus clear skies and exceptional surface flatness make the Salar an ideal object for calibrating the sensors of the Earth observation satellites.

The aim of the present work is to present the state of the art of the satellite monitoring and alert system, that will allows to follow the variability of the water covered area of the Poopo-UruUru lake system as well as both Salars (Coipasa and Uyuni). After a presentation of the methodology applied for computing the different maps of water covered areas, we will, based in this information show an analysis of its variability throughout the last decade.

The Poopo-UruUru lake system itself is located geographically within 18º21'- 19º10' S and 66º50'- 66º24' W, at an average mean high of about 3686 meters. Its extent is an average of 91 km long from the Desaguadero River (which connects the lake with the Lake Titicaca at the north end of the Altiplano) down to the River Marquez in the south while being an average of 32-to-59 km wide. The Poopo-Uru system is in fact constituted of two interconnected lakes (The Uru-Uru and Poopo), connected by a very narrow channel. As these lakes are very shallow, Poopo depths evolves only between 0.5 and 2.5 meters, together it encompass a mean area of about 3084 km2 and presents thus a greater seasonallity highly dependent on the hydrologic recharge period that takes place during December-to-March, which surplus can oscillate between 1000 to 2000 km2. Thus in period of strong precipitations, the lake volume reaches 2569 million m3, while reaching hardly half during normal times.

Thus, concerning the Poopo-UruUru Lake system, complementary analysis of satellite mission data (altimetry, MODIS) and climate fields over 2000 to 2009 were conducted to investigate the variability of the water cover surfaces and the geographical source of water inflowing into the Lake Poop> system. Interestingly, the results suggest that over the time span 2000-2009 a great part of the variability of the Poop> system originates from geographic sources other than Lake Titicaca, as was thought until recently. Possible alternative causes include climate change inducing increased temperatures and greater evaporation rates along the Altiplano and increased glacier and snow melting over the Andes Cordillera, and a potential increased anthropogenic water use (such as irrigation, minery, etc.) throughout the path of the Desaguadero River (which connects Lakes Titicaca and Poopó). This change in the hydrology of this region could lead to a collapse of water supplies and endanger the already fragile Poop> system, as well as the regional socioeconomic system, which closely depends upon it.

Concerning the Salars, the same complementary analysis, over the same time span (2000 to 2009) allows also to detect water cover surfaces periods and discern better the origin of precipitation variability on interannual time scales, and link main extremes to indexes of climate variability.

This work was part of the ECOS C04U02 (Chile-France) project > continental hydrology from a combination of altimetry, gravimetry and in-situ data. Application to the Andean Region. >

Using Radar Altimetry to update a Hydrological Model of the Zambezi River Basin

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Satellite radar altimetry allows for the global monitoring of surface water elevations of lakes and rivers. This type of global dataset is provides valuable information, especially in areas with sparse or no *in situ* gauging networks. However, the widespread use of radar altimetry datasets for hydrological studies is limited by the coarse temporal and spatial resolutions provided by current altimetric missions and by the fact that discharge rather than level is typically the variable of interest for hydrological applications. One way to overcome these limitations is the use of altimetric river level time-series combined with hydrological modeling in a data-assimilation framework in order to improve short-term streamflow forecasts.

This study focuses on the updating of a river routing model of the Zambezi using river level time series from radar altimetry at different locations in the basin. A hydrological model of the Zambezi River basin was built with the Soil and Water Assessment Tool (SWAT) and forced using remote sensing data to simulate the land phase of the water cycle and produce inflows to a Muskingum routing model. The inflows to the routing model are uncertain due to uncertain forcing, model structure and parameterization in the SWAT model. River altimetry from the Envisat mission was then used to update the storages in the reaches of the Muskingum model using the Extended Kalman Filter. The method showed improvements in modeled flows relative to the case with no data assimilation.

Improvement in discharge Estimates in a Remote ungauged Basin by including space Data Information into a hydrological Model

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Hydrological models need a large amount of information to be calibrated, and also require the user to have a high level of knowledge of the study area. But, in the case of tropical countries and basins, the amount of in-situ information is usually poor, for both societal and natural reasons. In such a case of a remote poorly gauged basin, the lack of input data is usually overcome by use of empirical laws or statistical (climate) information that do not always contain the required amount of space and time information for the flow prediction to have the expected level of accuracy. Today, spatial data like altimetry, rainfall global fields, inundation or vegetation cover maps, etc, have global coverage and span over years, even decades. Therefore, such data can play a major role in improving the accuracy of the current hydrological modeling.

In the present work, we present the benefits of using spatial products like altimetry and rainfall rate for tuning and running the IPH-MGB hydrological model. The study area is the Japura-Caqueta sub-basin, in the Amazon basin. It is a trans-boundary basin, shared by Colombia, upstream and Brazil, downstream. The geography of this 250,000 km^2 varies from rain forest to high mountains (Andes). Discharge at the mouth ranges from 3,000 to more than 25,000 m3/s. This remote basin is poorly monitored. Only two gauges are available all along this 2100 km long river. Yet, almost no data (water stage, discharge, rainfall...) is actually available in the Colombian part. First data are collected at the frontier, 1300 km after the spring.

The MGB model uses rainfall rate, vegetation coverage, soils characteristics and river channel geometry to compute discharge. The information gained from space includes time series of altitude and river slope from the ENVISAT mission, and TRMM rainfall rate. Altimetry information is used to tune the model, and rainfall rates are used as input to the model. Model performance are evaluated by comparing the model and gauge discharges

The use of TRMM rainfall rate instead of data interpolated from the few nearest in-situ pluviometers improved model's results by 30% in term of error in volume and 50% in term of Nash-Sutcliffe coefficient. The impact of the altimetry data is discussed for different options used to tune the model. Using manning's equation and assuming a rectangular cross section, simulated water heights can be calculated from simulated discharge and compared to altimetric water heights. Then, the new parameters issued from the transformation of discharge into water heights are included into tuning process in addition to common model parameters, for a better representation of water stages.

ACE2 Validation and Future Look

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Altimeter Corrected Elevations 2 (ACE2), released in 2009, is the Global Digital Elevation Model (GDEM) created by fusing the high vertical accuracy of over 100 million retracked altimeter height estimates, derived primarily from the ERS-1 Geodetic Mission, with the high frequency spatial content available within the near-global Shuttle Radar Topography Mission. This novel ACE2 GDEM is freely available at 3", 9", 30" and 5' and has been distributed via the web to over 520 subscribers. This paper presents the validation of ACE2 heights by comparison with independent datasets. Firstly, the height database derived from the Jason-1 Poseidon-3 altimeter was utilised; a global comparison with Jason-1 demonstrated good agreement between the two datasets, with a mean difference of 43cm. Secondly, the detailed Australian ANUDEM dataset compiled from ground survey information was compared. ANUDEM is a highly accurate DEM, with a resolution of 9". ACE2 data were compared on a 1-to-1pixel basis, with mean agreement between the two datasets of 2.76m.

The new EnviSat 30-day orbit has made information available over areas previously devoid of altimeter data. Thanks to its mode switching capability, EnviSat is able to provide results over rough terrain, enhancing the capability of the altimeter to inform DEMs. Results from a comparison of retracked 30-day EnviSat altimeter data with ACE2 are also presented.

This paper also quantifies the potential future benefits of the new generation of radar altimeters, and how such observations might inform the development of ACE3. Comparison of the EnviSat Burst Echoes with the 1" SRTM and the recently released 1" ASTER dataset, derived from stereo-optical remote sensing, demonstrates the impact of a higher Pulse Repetition Frequency, and what benefits this can provide in the context of DEMs. Further to this, an analysis of a CryoSat-2 CRYMPS simulator scenario over wetlands was performed to assess the potential of the new SAR Full Bit Rate (FBR) data over areas of rapidly varying terrain, along with initial results from SAR FBR data over the Mekong Delta to make an initial assessment of the augmented height measurement capability.

Potential of radar altimetry for estimating soil moisture

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We analyse the potential of the radar altimeter onboard ENVISAT for the estimation of surface soil moisture in the semi-arid Gourma region (Northern Mali). To this end, the relationships between observed backscattering coefficients derived from 4 retracking algorithms, namely Ocean, Ice-1, Ice-2 and Sea-Ice, and ground data, including soil type, topography, vegetation and soil moisture are investigated. The considered period is 2002-2010. Results show a strong linear relationship between the backscattering coefficients and surface soil moisture measured at six different stations along the satellite track. The best results are obtained with the Ice-1 and Ice-2 algorithms. In these cases, correlation coefficients are higher than 0.8 with RMSE smaller than 2%. Vegetation effects are found to be small due both to the nadir-looking configuration of the radar altimeter and to the low vegetation cover. The relationship between soil moisture measured in situ and normalized backscattering coefficient is then applied to retrieve soil moisture from the altimeter data. Altimetry-based soil moisture estimates are compared with these obtained by electromagnetic modeling for different type of soils (characterized by their dielectric constant and their roughness), bare or covered with vegetation, in Ku, C and S bands. These results highlight the high capabilities of Ku-band altimeters to provide an accurate estimation of surface soil moisture in semiarid regions.

ICESat Altimeter Data for Gauge Datum Correction and Hydraulic Model Validation

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In this paper we demonstrate the potential utility of the Geoscience Laser Altimeter System (GLAS) instrument on board the Ice, Cloud and land Elevation Satellite (ICESat) for applications in hydrology. In particular, we focus on two tasks: the development of consistent and accurate gauge datum levels for continental scale river systems and the use of the GLAS data for the calibration and validation of large scale hydraulic models of remote river basins. For geodetic levelling of gauge sites we show the accuracy of the method by comparison to precisely known datum levels in the Danube system, before demonstrating the potential utility of the technique in a more remote basin setting (the Brazilian Amazon) where datum levels are not so well tied to the geoid. The results are significant, with offsets as large as 13.37 m being added. The Danube study also provides evidence that ICESat data can be used for the calibration and validation of large scale hydraulic models in remote basins where gauge networks are declining and data are either sparse or non-existent. Despite the intermittency of the ICESat data, sufficient information still exists to capture the dynamic flood pulse in large river systems and robustly test the performance of hydraulic models created using SRTM terrain data. Accordingly, we present two proof of concept applications from basins in Africa: the Niger River in Mali and the Zambesi River in Southern Eastern Africa.

Oceanography – Integrated Systems – Applications – Forecast – Assimilation II

A Revised Estimate of Upper Ocean Heat Content in Light of a New XBT Bias Correction and Implications for the Global Energy Bala

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The oceans absorb the vast majority of any net radiative imbalance in the global climate system, such as the one caused by the addition of anthropogenic greenhouse gases to the atmosphere. For this reason, quantifying the accumulation of heat in the global oceans provides important insight into the accumulated impact of human-caused climate change. Past estimates of ocean heat content increase have suffered from biases in one of the most abundant sources of ocean temperature data, the eXpendable BathyThermograph (XBT). Although a number of recent estimates of historical ocean heat content have been produced based on new bias estimates, it has proven difficult to remove all of the bias in the historical XBT data set. As a result, remaining XBT biases still account for significant discrepancies between different estimates of ocean heat content on interannual time scales. Here, a new estimate of ocean heat content is produced using a newly developed XBT bias correction that accounts for both temperature offsets as well as time-varying changes in the fall rates of XBT probes. Both types of biases are assessed using satellite observations of both sea surface temperature and sea surface height since the early 1990s. Finally, the new estimate of ocean heat content will be compared with recently published estimates of the net global radiative imbalance as observed by satellite.

Sea Level Trends in Ocean Reanalyses/Syntheses

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Ocean reanalyses/syntheses combine information about the time-dependent response of the ocean to surface heat, momentum, and freshwater fluxes from a numerical simulation model with information from observations of variables such as temperature, salinity, and sea level. Done correctly, the result is an improved analysis of the evolving state of the ocean. The results from different reanalyses/syntheses vary since they may include radically different assumptions, models, and data sets. One such system includes eustatic, loading, and self-gravitation effects. Most, including SODA, currently do not. This paper will

compare estimates of sea level and dynamic topography from a variety of ocean reanalyses/syntheses in comparison with observed satellite and gauge sea level records particularly focusing on those reanalyses/syntheses which span multiple decades. A key goal is to explore differing estimates of the geographical variations in the thermosteric and eustatic contributions to sea level and their connections to changes in ocean circulation. By comparing the reanalyses/syntheses to land-based gauges we will provide independent estimates of GIA. We will also explore what information the reanalyses/syntheses can provide of the uncertainties associated with detection of centennial trends and acceleration in global sea level.

Evaluating an Ensemble of Global Ocean Circulation Estimates using Satellite Altimetry, Gravity Field Models and Argo data

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We compare an ensemble of ocean circulation hindcasts for years 1993 to 2007 to geodetic estimates of dynamic topography and in situ measurements of temperature and salinity (ARGO). Dynamic topography is based on multi-mission altimetry referenced to the GOCE geoid. The hindcasts are simulated by FESOM, a general circulation ocean / sea-ice model on unstructured meshes with spatially variable resolution. It allows to refine areas of particular interest in the global context. The ensemble members differ slightly by atmospheric forcing, by their initial states and/or by the model meshes. Refinement was done in various key regions for the large scale ocean circulation, such as equatorial belt, Denmark Strait, and the mean background resolution.

We compare the model trends in sea level and steric height. Results show that the ensemble mean trend pattern at large compares with observations. The estimated mean and spread in sea level as well as steric height are discussed in comparison to observations.

Understanding Decadal Changes In Regional Sea Level Patterns And Their Causes In A Data-Constrained Ocean General Circulation Model

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Given costly impacts they may have on coastal zones and valuable insight they can provide into the variable ocean circulation and climate, recent decadal trends in regional sea level have been the focus of great interest, fueling attempts to attribute the dynamic and thermodynamic causes of observed regional changes. Based primarily on a number of simple modeling studies, it is commonly thought that regional trends mostly reflect thermosteric variations (i.e., ocean heat content changes) brought about by wind-driven changes in the ocean general circulation. To consider more comprehensively causal mechanisms of recent regional sea level trends, we make use of a dynamically consistent, multi-year ECCO (™Estimating the Circulation and Climate of the Ocean") general circulation model solution, constrained to altimetry, in situ hydrography, and other observational datasets via the method of Lagrange multipliers. By means of numerical forcing experiments and closed steric sea level budgets, regional trends are ascribed to various physical processes (e.g., local atmospheric forcing and ocean transports) and forcing mechanisms (e.g., time mean and variable winds and surface buoyancy exchanges). Buoyancy forcing can exert local and remote influence on trend patterns, signaling the importance of considering a variety of forcing mechanisms, including-but not limited to-the winds. The influence of parameterized mixing processes is widespread, pointing to a need to understand better the importance of eddy fluxes on sea level trends and determine the realism of sub-grid-scale parameterizations of these effects in ocean models. Contributing processes (e.g., temperature and salinity changes, buoyancy- and wind-forced transports) can have compensating effects on sea level trends, suggesting that regional sea level trends may not be a good indicator of changes in other climate parameters in some regions. Additionally, due to spatial and temporal variations in thermal expansion coefficients, ocean transport processes make significant contributions to globally averaged sea level changes.

Global Eddy-Permitting Ocean Reanalyses and Simulations of the Period 1992 to Present

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The GLORYS (Global Ocean reanalysis and Simulation) Project is motivated by the need of a realistic description of the ocean state and variability over the recent decades, at the global scale, and at the scale of the ocean basins and regional seas. The French research community (CNRS), the operational ocean forecasting center Mercator Océan and the CORIOLIS data center, have gathered their skills and expertise in physical oceanography, ocean modeling and data assimilation, to carry out global ocean reanalyses at eddy scale resolution for the period 1993 to present. This reanalysis effort is part of the project MyOcean granted by the European Commission within the GMES Program (7th Framework Program).

This paper will present the GLORYS reanalysis system relies on the ORCA025 global model configuration developed by the DRAKKAR consortium, on the basis of the NEMO3 ocean/sea-ice general circulation model. ORCA025 uses a horizontal grid resolution of 1/4º and 75 vertical levels, which permits the growth of mesoscale eddies. It is used for both operational and climate applications. The data assimilation scheme is an adaptation of the data assimilation scheme used for operational forecasting by Mercator Océan. The data assimilation method is based on a reduced order Kalman filter (SEEK formulation) and an incremental analysis update, in conjunction with a bias correction scheme for temperature and salinity. Assimilated data are from the delayed time CORA data base specifically prepared for ocean reanalysis by the CORIOLIS data center, and from AVISO for altimetric data. Sea Surface Temperature, along track Sea Level Anomalies and in situ Temperature and Salinity profile data are assimilated. GLORYS reanalyses are forced with atmospheric surface variables from ERA-INTERIM atmospheric reanalysis, and control simulations with no observation assimilated are systematically produced.

Two reanalyses and one reference simulation with no data assimilation have been produced, validated and are distributed. The first one, GLORYS1, covers the "Argo era" (2002-2008). The second one, GLORYS2, covers the "altimetric era" (1992-2009) and will be updated until 2011. The reference simulation also covers the "altimetric era, and uses the exact same atmospheric forcing as GLORYS2. The paper will present assessments and measures of the quality of GLORYS products obtained from a validation protocol based on recommended GODAE and CLIVAR-GSOP reanalysis diagnostics, and from a comparison with the reference experiment. The scientific value of the GLORYS reanalysis products will be illustrated with results from independent scientific studies obtained in a wide range of areas such as climate, mesoscale processes, mixed layer processes, sea ice, etc.

Imprint of the Intrinsic Low-frequency Ocean Variability on Satellite Observations and Climate Indices.

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Under constant or seasonal atmospheric forcing, the eddying ocean spontaneously generates 1-10 year variability that particularly affects the horizontal circulation. Idealized studies (see the review by e.g. Dijkstra and Ghil, 2005) have shown that this nonlinear phenomenon is chaotic and gets stronger with increasing Reynolds number. Processes have been proposed to explain its generation, e.g. eddy-eddy interactions (Arbic et al. 2012), eddy PV fluxes or turbulent rectification (Spall 1996; Dewar 2003; Berloff et al 2007).

Identifying the magnitude, spatial structure and various fingerprints of this intrinsic chaotic variability in the real ocean would have important implications (e.g. for satellite-based and in-situ climate monitoring, numerical hindcasting/forecasting, ocean model assessment, etc). This can hardly be done from observations only since intrinsic and atmospherically-forced ocean variabilities are entangled; however this is being done from recent global, high-resolution, multi-decadal Ocean General Circulation Model simulations.

In this study, we address the issues mentioned above by comparing a 327-year seasonally-forced simulation (no interannual forcing) performed with the Drakkar NEMO-based global 1/4º model (Penduff et al., 2010), with its 50-year counterpart driven by a realistic forcing including the full range of timescales (i.e. with interannual forcing).

Our seasonally-forced simulation reveals the imprint of the intrinsic interannual variability on various observed and climate-relevant ocean variables, e.g. sea-level anomalies (Penduff et al., 2011), sea-surface temperature, mixed layer depth, meridional overturning circulation. Comparing these intrinsic variances with their total counterpart (from the second simulation) then provides us with estimates of this chaotic component's fingerprint on actual interannual variabilities.

We show that intrinsic variances, which are negligible in laminar IPCC-like (~2º) ocean models, may exceed their atmospherically-forced counterparts in eddying regions and leave a large imprint on several climate-relevant variables, in particular at the sea-surface that is observable by satellite (in particular altimetry). This raises important issues about ocean and climate variabilities in future IPCC climate predictions, which will employ eddying ocean models.

Oceanography – Mesoscale I

Beta-Plumes and Origin of striated Patterns in the Ocean

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Dynamics of "striations", quasi-zonal jet-like features seen on maps of multi-year mean geostrophic velocity, is analyzed in the framework of beta-plumes, ocean circulations generated by localized sources of vorticity. Beta-plumes are exemplified in the ocean by the Azores Current induced by the outflow of Mediterranean water from Gibraltar, the Hawaiian Lee Countercurrent generated by the orographic wind stress curl in the lee of Big Island of Hawai'i, and features off of the California coast resulting from nonlinear interaction between baroclinic meander of the California Current and Ekman flow. Experiments with the idealized ROMS model demonstrate formation of the system of jets west from the source area in linear regime and of system of eddy trains in nonlinear regime. In the presence of the background meridional flow, common in the regions populated by striations, beta-plumes change in two ways: orientation and generation of eddies. Axes of beta-plumes are tilted by the large-scale advection in the same manner both in linear and non-linear regimes. In linear case, tilted axes allow trapped Rossby waves to propagate meridionally against the flow. In nonlinear case, the tilt is achieved by a superposition of westward drift of eddies and their meridional advection by the flow. Due to instability of meridional flow, new eddies are generated not only in the beta-plume vorticity source but also along the jets west from the source area. Both the tilt of striations, consistent with the direction of the large-scale flow, and formation of eddies away from eastern boundaries are confirmed using altimetric maps of the sea level anomaly. New eddies are shown to form preferentially on crests and troughs of pre-existing striations. This complex organization of eddies is also confirmed by the structure of space correlation functions of geostrophic velocity and vorticity. The functions combine "eddy" correlations, suspiciously coinciding with the AVISO mapping functions, and long-rage correlations extending up to 2000 km in the zonal direction and including a set of crests in the meridional direction. This study demonstrates how originally simple physic of a beta-plume, when placed into realistic conditions of unstable ocean gyres, develops complex organization of mesoscale eddies, which both results from and visualizes the striated pattern of the plume. Figure. 1993-2002 mean zonal surface geostrophic velocity high-pass filtered with a two-dimensional Hanning filter of a 4-degrees half-width. Units are cm/s.

Use of Satellite Data with Dynamical Concepts to Diagnose the Fine Resolution Ocean Dynamics in the first 500m Below the Surface

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We introduce in this presentation new ideas to retrieve the ocean mesoscale and submesoscale dynamics, in the first 500m below the surface, using both satellite altimetry and sea surface temperature as well as existing in-situ data such as those from Argo floats.

The diagnosis dynamical method rely on the 3D inversion of potential vorticity whose knowledge can be estimated from satellite altimetry and in-situ data, as developed in Lapeyre and Klein (JPO, 2006) and Klein et al. (GRL,2009). The new ideas take into account the mixed-layer dynamics, which allows to much better integrate the sea surface temperature information in the diagnosis dynamical method.

These ideas have been tested using primitive equation numerical simulations at high resolution either in the Antarctic Circumpolar Current or the North Pacific.

Mean-flow and Topographic Control on Surface Eddy-mixing in the Southern Ocean

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Surface cross-stream eddy diffusion in the Southern Ocean is estimated by monitoring dispersion of particles numerically advected with observed satellite altimetry velocity fields. To gain statistical significance and accuracy in the resolution of the jets, more than 1,5 million particles are released every 6 months over 16 years and advected for one year. Results are analyzed in a dynamic height coordinate system. Cross-stream eddy diffusion is highly inhomogenous. Diffusivity is larger on the equatorward flank of the Antarctic Circumpolar Current along eddy stagnation bands, where eddy displacement speed approaches zero. Along such bands, diffusivities reach typical values of 3500 m2 s−1. Local maxima of about 8−12.103 m2 s−1 occur in the energetic western boundary current systems. In contrast, diffusivity is lower in the core of the Antarctic Circumpolar Current with values of 1500-3000 m2 s−1, and continues to decrease south of the main ACC system. The regional structure of eddy diffusion is strongly influenced by topography. Mean-flow and topography shape the global structure of Southern Ocean mixing by reducing diffusion in the core the Antarctic Circumpolar Current and by increasing mixing on its northern flank along the stagnation bands, themselves partly controlled by topography, and in the wake of obstacles.

Can We Infer Ocean Dynamics from Altimeter Wavenumber Spectra?

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The wavenumber spectra of sea surface height (SSH) and kinetic energy (KE) have been used to infer the dynamics of the ocean. When quasi-geostrophic dynamics (QG) or surface quasi-geostrophic (SQG) turbulence dominate and an inertial subrange exists, a steep SSH wavenumber spectrum is expected with k-5 for QG turbulence and a flatter k-11/3 for SQG turbulence. However, inspection of the spectral slopes in the mesoscale band of 70 to 250 km shows that the altimeter wavenumber slopes typically are much flatter than the QG or SQG predictions over most of the ocean. Comparison of the altimeter wavenumber spectra with the spectra estimated from the output of an eddy resolving global ocean circulation model (the Hybrid Coordinate Ocean Model, HYCOM, at 1/25° resolution), which is forced by high frequency winds and includes the astronomical forcing of the sun and the moon, suggests that the flatter slopes of the altimeter may arise from three possible sources, the presence of internal waves, the lack of an inertial subrange in the 70 to 250 km band and noise or submesoscales at small scales. When the wavenumber spectra of SSH and KE are estimated near the internal tide generating regions, the resulting spectra are much flatter than the expectations of QG or SQG theory. If the height and velocity variability are separated into low frequency (periods greater than 2 days) and high frequency (periods less than a day), then a different pattern emerges with a relatively flat wavenumber spectrum at high frequency and a steeper wavenumber spectrum at low frequency. The stationary internal tides can be removed from the altimeter spectrum, which steepens the spectral slopes in the energetic internal wave regions. Away from generating regions where the internal waves are weaker than the QG flow, then the high frequency motions have little impact on the wavenumber spectrum. However, the spectral slope estimates are sensitive to the wavenumber range and altimeter noise. When the mesoscale KE is small, the peak of the enstrophy (mean square vorticity) moves to small scales and the mesoscale band of 70 to 250 km no longer represents the inertial subrange. At small scales the altimeter wavenumber spectra are much flatter than the model spectra which may be the result of noise or submesoscale motions. The model doesn't resolve submesoscale motions which tend to increase the KE at small scales and may explain why the model spectra are much steeper than the altimeter spectra at small scales. However, adding white noise corresponding to the altimeter spectral level at the smallest scales flattens the model spectra similar to the observed altimeter spectra. Thus, it is difficult to infer the ocean dynamics from the altimeter spectral slope over a fixed wavenumber band.

Impact of Horizontal Resolution on Ocean Surface Energy Cascades Computed in Frequency and Wavenumber Domains

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We compute spectral fluxes of ocean surface geostrophic kinetic energy in both the wavenumber and frequency domains, from 16 years of AVISO gridded satellite altimeter data, from idealized quasi-geostrophic (QG) simulations, and from primitive equation models run in near-global realistic domains. The spectral fluxes identify the importance of nonlinearities in maintaining the wavenumber and frequency spectra. Fluxes are computed from both unfiltered and filtered output of the QG and realistic models, where the filtered output is meant to crudely mimic the spatial and temporal filtering inherent in the creation of gridded AVISO data from raw along-track altimeter data.

The addition of eddy viscosity, meant to crudely mimic the transfer and subsequent dissipation of energy from mesoscale eddies to internal gravity waves and submesoscale motions, leads to a forward energy cascade at small scales in the QG model, in apparent agreement with spectral fluxes computed in wavenumber space from altimeter data (Scott and Wang 2005). However, spectral fluxes in wavenumber space computed from the filtered output of either QG or realistic models also display a forward cascade at small scales. Thus at present it is difficult to tell whether the forward fluxes seen by Scott and Wang are physical or represent sampling artifacts.

The QG model, realistic model, and AVISO altimeter data all display a qualitatively similar frequency spectrum, with steeper slopes at higher frequencies and flat spectra at lower frequencies. In the QG and realistic models the fluxes computed in frequency space demonstrate an "inverse temporal cascade", i.e. a tendency for nonlinearity to drive energy towards lower frequencies as well as lower wavenumbers. In the altimeter data, the "inverse temporal cascade" seen in the QG and realistic models is seen in some regions. In other regions the "inverse temporal cascade" is not seen. However, once again, filtering exercises with the models demonstrate that the fluxes computed from altimeter data may suffer from sampling problems. Thus at present it is difficult to tell whether the disagreement between models and AVISO data regarding nonlinear cascades of geostrophic kinetic energy in the frequency domain are due to real physics missing from the models, or to sampling artifacts in the data.

Past, Present, and Future Developments in Rossby Wave Theories and Observations

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Satellite altimetry has over the past 20 years revolutionized our understanding of Rossby waves, by revealing their ubiquitous existence in all ocean basins at nearly all latitudes at unprecedented temporal and spatial resolutions. These new observations have provided the incentive for a renewal of interest in the theoretical study of how topography, the background mean flow, nonlinearities, all affect the propagation of oceanic Rossby waves and eddies, initially motivated by the "too-fast" Rossby wave riddle. Subsequent theoretical developments provided new insights into how barotropic and baroclinic waves interact over topography, how baroclinic instability and/or linear dispersive effects limit the westward propagation of boundary-driven waves, how the topography and mean flow can both contribute to surface-intensify Rossby waves, how nonlinearities and/or a background mean flow may render the waves quasi-nondispersive at high wavenumbers. As Rossby wave theories become increasingly realistic, and the quality and resolution of observations increase, there is increasing interest in understanding whether they can be used to project meaningfully the surface observations onto the vertical, which is a central issue in data assimilation. Testing such ideas, however, requires using high-resolution numerical ocean models to access the information about the vertical structure, in complement of the sparse information provided by ARGO floats. In this talk, I'll review the theoretical progress achieved, and discuss future directions of research.

Marine Geodesy, Gravity, Bathymetry and Mean Sea Surface

20 Years of Marine Gravity Mapping from Altimetry and its Impact on Improvements in Altimeter Range Precision

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Sea level (geoid) anomalies at scales of 10 to 100 km can reveal the topography of the sea floor. Resolution of these anomalies requires altimeter profiles of sea surface height along a densely spaced network of ground tracks. Such networks have been acquired only 3 times in the history of altimetry: in 1985-86 by the then secret Geosat Geodetic Mission, in 1994-95 by the ERS-1 geodetic phases E and F, and since 2010 by CryoSat. The first results appeared in 1992 when circum-Antarctic gravity anomaly maps were published following the release of Geosat GM data south of 60 degrees south in 1990 and south of 30 degrees south in 1992. A bathymetric map of the southern ocean estimated from altimetry followed in 1994. In late 1994 a launch failure delayed the planned launch of ERS-2, enabling the ERS-1 geodetic mission to proceed to completion in March of 1995, and allowing high-resolution marine gravity mapping to extend to all the oceans. The results were shown at the 1995 Spring AGU meeting and this may have prompted the U.S. Navy to release all the Geosat GM data, which were made available in August of 1995. The results have been a boon to mapping the mean sea surface, geoid, gravity anomalies, and bathymetry. Highlights will be shown in this talk.

Over the last 20 years physical oceanographers have enjoyed a plethora of exact-repeat missions (ERS-1, ERS-2, Envisat, Topex/Poseidon, Jason-1, Jason-2, GFO) while until the launch of Cryosat the only geodetic data remained the Geosat GM and ERS-1 phases E and F. Geodesists therefore have spent the last 15 years improving the Geosat and ERS-1 data. The spatial resolution of geodetic altimetry is limited by the random noise level in the radar range measurement, and geodesists made many advances in retracking algorithms, cutting range error nearly in half, and leading to improvements that have been a benefit to oceanography. Geodetic needs also pushed the development of altimetry. The 'ABYSS' mission, proposed to NASA in 2001, would have carried a delay-Doppler (SAR) altimeter with multi-looked on-board processing for a four-fold improvement in geodetic altimetry worldwide. Aspects of the delay-Doppler concept are the basis of the SAR modes of CryoSat, Sentinel-3, and Jason-CS.

CryoSat presents the first new ocean mapping opportunity since ERS-1 in 1995. Although it covers most of the ocean only in conventional 'low resolution mode' (LRM), the signal-to-noise ratio in CryoSat's LRM range measurements is better than that of Geosat and ERS-1, and this is leading to improved resolution of north-south gravity anomalies. Improved resolution in the east-west direction will require an altimeter in a lower inclination, such as Jason-1, or a new dedicated mission, such as ABYSS or GRAL.

Using the GOCE Error Covariance Products to improve Geodetic Estimates of the Ocean's MDT and Geostrophic Currents

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Over the last decade, the GRACE and GOCE satellite missions, together with on-going refinements in satellite altimetry, have produced a dramatic improvement in the ability to measure the ocean's mean dynamic topography (MDT) from space. Yet, what has hitherto been lacking is a rigorous means of determining the accuracy of the computed MDT over its full range of spatial scales. The GOCE mission has gone some way to addressing this gap by providing formal error estimates for the Earth gravity models delivered by the mission's High level Processing Facility (HPF). Here, we show how these GOCE error products can be exploited in a number of ways crucial to improving still further geodetic MDT estimates. The basis of the analysis presented is the surprisingly good agreement we find between formal geoid error estimates, obtained by error propagation from the full error covariance products, and informal, heuristic MDT error estimates.

First, this close correspondence is used to provide a novel and independent oceanographic perspective on the quality of the earth gravity models themselves, allowing a comparison between the various approaches to determining the gravity field, and an assessment of how the quality of the models has improved as a function of data collected. Second, the agreement is used to rigorously assess and select between various approaches to determining the MDT, showing the strengths and weakness of each approach and illuminating the path towards further improvements in the geodetic MDT computation. In spite of these steps forward, some filtering is still required to remove short length-scale errors, or noise, in the computed surface. This otherwise hampers the determination of the geostrophic ocean currents associated with the MDT. Finally, therefore, it is demonstrated how the formal errors can be employed in a strategy for determining the degree of filtering that should be applied to the dynamic topography to obtain the best possible estimate of ocean currents.

Mean Sea Surface and Dynamic Topography of the Arctic Ocean from Envisat and ICESat

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Envisat's Radar Altimeter-2 (RA-2), and the Geoscience Laser Altimeter System (GLAS) that was carried on ICESat, provide measurements of both sea-ice elevation and the instantaneous sea surface height (SSH) of the Arctic Ocean. Discrimination of elevation measurements from open water and leads within the ice-pack provides, over time, details of both the mean and time-variable components of Arctic SSH. Knowledge of the mean sea surface (MSS) in particular is critical for investigating Arctic Ocean geostrophic circulation. In this study, SSH profiles were generated by stacking and averaging along-track altimetry data gathered between March 2003 and October 2009. The Envisat and ICESat data were then combined to compute the high-resolution "ICEn" MSS which spans the Arctic Ocean from 60 to 86 °N. By differencing the ICEn MSS with the new GOCO02S geoid model, derived from a combination of GOCE and GRACE gravity, we estimate the 5.5-year mean dynamic topography (MDT) of the Arctic Ocean. We will show that the combination of satellite altimetric and gravimetric data improves our ability to estimate Arctic MDT. Specifically, we will demonstrate that the satellite-only data can be used to map the major features of Arctic Ocean dynamical height and geostrophic currents that are consistent with in situ observations. This includes the topographical highs and lows of the Beaufort and Greenland Gyres, respectively. We will discuss the remaining uncertainties in the current state-of-the-art Arctic marine geoid models and their impact on our ability to resolve smaller-scale MDT structures.

A Factor of 2 Improvement in Global Marine Gravity and Bathymetry from CryoSat and Envisat Altimetry

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Marine gravity anomalies derived from radar altimeter measurements of ocean surface slope are the primary data for investigating global tectonics and seafloor bathymetry. The accuracy of the global marine gravity field is limited by the availability of non-repeat altimeter data. Current models, having accuracies of 3-5 milligals (e.g., S&S V18 and DNSC08), are largely based on the non-repeat data collected by Geosat (18 mo.) and ERS-1 (12 mo.) which use altimeter technology from the 70's and 80's, respectively. Recently two new non-repeat altimeter data sets have become available from Cryosat and Envisat in its 30-day "drifting" phase. To optimize gravity field recovery from all four altimeter data sets, we have developed a two-pass retracking algorithm that improves the range precision by a factor of 1.3-1.5 depending on sea state. The retracking has been applied to: 18 mo. of Geosat from its geodetic phase; 12 mo. of ERS-1 from its geodetic phase and 6 mo. from its 35-day repeat phase; 6 months of Envisat from the 35-day repeat and 18 months from its new 30-day repeat; and 24 months of Cryosat using all three modes (LRM, SAR, and SARIN). We find that the range precision of Envisat is 1.4 times better than ERS-1 perhaps due to its higher pulse repetition frequency. Moreover Cryosat LRM data are up to 2 times better than ERS-1. These improvements in range precision, combined with 4 additional years of non-repeat coverage from Envisat and Cryosat, improve the accuracy of the global marine gravity by nearly 2 times. The improved accuracy is confirmed using gravity profiles collected by research vessels.

At the meeting we will release a new 1-minute global marine gravity model (V19.1) as well as a new global bathymetry model (V15.1). Preliminary versions of these models are beginning to resolve the abyssal hill fabric on the flanks of the slower-rate spreading ridges as well as thousands of previously unmapped small seamounts. One of the more interesting discoveries from the new gravity model is N-S trending fractures in the seafloor east of Tahiti that appear to be younger than the original seafloor spreading fabric. Confirmation of these features would provide evidence for large-scale deformation of the Pacific plate.

The MSS from Satellite Altimetry and its Improvement During the past 20 Years

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The mean sea surface (MSS) is an important parameter in geodesy and physical oceanography. It is the time-averaged physical height of the ocean's surface. The challenge in MSS mapping is to achieve the most accurate filtering of the temporal sea surface variability with a limited time span and simultaneously obtaining the highest spatial resolution. This is normally achieved by combining data from the highly accurate exact repeat mission (ERM), with data from the older non-repeating geodetic mission (GM) like ERS-1 and GEOSAT.

Since 1996, several determinations of sea surface have been made globally at both the Center of Space Research (CSR-UTexas), at Ohio State University, at the KMS/DTU in Denmark and at Collecte Location Satellite (CLS) in France. The first versions of the MSS was calculated using only 3 years of altimetric data, but as more and more altimetric data have been come available the most recent mean sea surface are produced using up to 18 years of satellite altimetry. MSS is by now a well-established correction that is applied to satellite altimetric to construct the sea level anomalies.

Different MSS will average different time intervals of the natural variation in sea level on inter-annual to longer time scales when they are derived. One example is CLS01 MSS and the CNES_CLS_2011 MSS which consistently use the 7 years between 1993 and 1999 in their derivation. Another example is DTU10 which uses 17 years of data (1993-2007).

For MSS determination the ERS-1 from 1994 and Geosat Geodetic mission data from 1985 are of paramount importance as these satellites are the only way of obtaining the spatial resolution of the finest geophysical structures at the shortest wavelengths with an interleave of 8 km at the equator and a sample of 7 km along tracks. It is not until the launch of Cryosat-2 that a new satellite offers the same spatial resolution as the old geodetic mission satellites. Data from Cryosat-2 will also add a new accuracy to MSS determination but globally but particularly in the Arctic Ocean where the new SAR altimetry enable retrieval of sea surface height in leads in the ice more accurate than before.

A two-decade Time Series of Eddy-resolving dynamic ocean Topography

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The significant improvements of GOCE derived gravity fields allows now to infer the dynamic ocean topography (DOT) by subtracting the geoid from sea surface heights (SSHs). While the geoid, derived from a band-limited gravity field model, is relative smooth and can be computed everywhere, the SSHs are observed along the altimeter ground tracks and exhibit high frequency variations. Thus, geoid and SSHs are to be consistently filtered. We apply a "profile method" performing such a filtering and subtraction along individual ground tracks. This way instantaneous DOT profiles (iDOT) can be generated for all ground tracks of any altimeter satellite. We apply this method to carefully cross-calibrated multi-mission altimetry available since 1993. Subsequently, the combined set of all iDOT profiles is gridded with 10-day sampling periods to construct a DOT time series spanning the period 1993 up to now. The high quality of GOCE gravity fields allows to reduce the filter length down to some 70 km such that the DOT time series resolves meso-scale Eddies. For the western boundary currents animations show the evolution of Eddies and of the associated geostrophic velocity field which in turn allows to infer the Eddy kinetic energy.

Oceanography – Integrated Systems – Applications – Forecast – Assimilation III

GODAE OceanView : Towards a Long-term International Program for Ocean Analysis and Forecasting

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The scientists leading the development of the major systems for generating real-time operational ocean forecasts, hindcasts and reanalysis constitute the inner core of the GODAE OceanView Science Team (GOV-ST). The primary goal of this team is to accelerate the improvement and exploitation of these systems through exchange of information and expertise and the coordination of joint assessments. Potential societal benefits of the exploitation of operational oceanography systems include improvements in the day-to-day management of coastal waters, the management of marine ecosystems, weather prediction from hours to decades ahead, and the expected impacts of climate change on the oceans and coastal waters. In order to foster the developments of such applications, task teams (TT) have been created within GOV: Coastal Oceans and Shelf Seas: COSS-TT, Marine Ecosystem Prediction: MP-TT and Short- to Medium-Range Coupled Prediction:SMRCP-TT. These TTs make the link between the inner core GOV-ST, and other teams outside GODAE OceanView working on these fields of application. The GOV systems results are critically dependent on both the satellite, including altimetry, and in-situ components of the GOOS. Through the development of improved Observing System Evaluations (OSEs) GOV contributes to coherent, effective and scientifically robust advocacy of the case for and prioritisation of the components of the GOOS. This work is conducted by the Observing Systems Evaluation TT (OSE-TT).

Finally, the Intercomparison and Validation TT (IV-TT) develops common assessment methodologies.

The hindcast and forecast systems developed by the GOV Science Team members both require inputs from and should be a valuable resource for the oceanographic research community. Support for cooperation between research and operational groups is a key element of GOV.

GOV, through the organisation of symposia and summer schools increases public awareness and knowledge about the Global Ocean Observing System (GOOS), the ocean modelling and ocean data assimilation science and technology, the real-time operational ocean forecast, hindcasts and reanalysis activities and their benefit to the society through related downstream services.

The GOV Science Team works on a five-year planning and review cycle and meets at least once a year. The workplan of the team has been published and can be accessed on GOV website www.godae-oceanview.org. Financial and in kind support required to run the project office, organize GOV-ST meetings, symposia and summer schools are provided by stakeholder agencies/groups. They are represented in the GOV Patrons Group which provides guidance to the GOV-ST, in addition to visibility and recognition of the value of GOV at national and international levels.

The Dependence of Short-range Ocean Forecasts on Satellite Altimetry

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Short-range ocean forecasting and reanalyses routinely combine observations from satellite altimetry, satellite sea surface temperature, and in situ temperature and salinity from Argo, XBT, and moorings, to initialise global and regional ocean models. Each data type provides independent information that helps represent different aspects of the ocean circulation. The most critical observation type for eddy-resolving applications is satellite altimetry – quantifying the variability of the mesoscale ocean circulation in time and space. Results from recently completed ocean reanalyses will be presented, showing that the accuracy of ocean reanalyses is directly related to the number and quality of satellite altimeters.

Implementing a 3D-VAR Data Assimilation System in the Met Office's Ocean Forecasting Model.

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The Met Office's Forecasting Ocean Assimilation Model (FOAM) has been run as a global operational system since 1997. The model produces analyses and forecasts of temperature, salinity, currents, sea surface height and sea ice. FOAM is run operationally in a global configuration at 1/4 degree resolution as well as in three nested 1/12th degree resolution regional configurations; the North Atlantic, Indian Ocean and Mediterranean models. The products are used by the Navy, commercially and for research purposes. Since 2008 the hydrodynamic model in FOAM has been the Nucleus for European Modelling of the Ocean (NEMO) model.

We are currently updating the data assimilation scheme in NEMO to the 3D-VAR system, NEMOVAR. This is replacing our current analysis correction data assimilation scheme in the operational system in autumn 2012. NEMOVAR is a multivariate incremental variational data assimilation scheme and is a collaboration between CERFACS, ECMWF, the Met Office and INRIA/LJK. The system assimilates SSTs from GHRSST, temperature and salinity profile data from Argo floats and other sources, altimeter SLA from AVISO and sea ice concentration from EUMETSAT. The system also includes an SST observation and altimeter bias correction scheme.

We will describe the implementation of NEMOVAR at the Met Office and will give an overview of the system. We will discuss how the different data types are assimilated in a coherent way using the balance relationships and will describe the specification of the error covariances. We will also show results from a NEMOVAR reanalysis and we will compare these to observations and results from our previous system.

Evaluation of Real Time and Future Forecasting Systems at Mercator Océan: Overview and Recent Improvements at the Global and Regional Scales.

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Since December 2010, the global analysis and forecast of the MyOcean system consists in the Mercator Océan NEMO global 1/4° configuration with a 1/12° "zoom" over the Atlantic and Mediterranean Sea. The zoom open boundaries come from the global 1/4° at 20°S and 80°N. This new system delivers weekly and daily services, and includes numerous improvements related to the ocean/sea-ice model and the assimilation scheme. The data assimilation uses a reduced order Kalman filter with a 3D multivariate modal decomposition of the forecast error. It includes an adaptative error and a localization algorithm. A 3D-Var scheme corrects for the slowly evolving large-scale biases in temperature and salinity. Altimeter data, satellite temperature, and in situ temperature and salinity vertical profiles are jointly assimilated to estimate the initial conditions for the numerical ocean forecasting.

In addition, two others systems are currently operated in real-time. Since August 2010, a global 1/12° system delivers weekly services. This system does not benefit from all recent improvements but offers a new perspective on the global ocean mesoscale predicting. Since March 2011, a high resolution system at 1/36° without assimilation, nested in the Atlantic and Mediterranean "zoom", covers Iberian-Biscay-Irish region. It includes high frequencies processes and is able to reproduce small structures like tidal fronts or upwelling filaments.

After a description of the recent systems, the validation procedure is introduced and applied to the current and future systems. It is shown how the validation impacts on the quality of the systems, and how quality check and data source impacts as much as the systems design (model physics and assimilation parameters).

All monitoring systems are close to Sea Level Anomaly (SLA) observations with forecast (range 1 to 7 days) RMS difference of 7cm. It is smaller than the intrinsic variability of the SLA observations. The dominant source of error in sea level comes from the uncertainty in Mean Dynamic Topography. The systems give an accurate description of water masses almost everywhere between the bottom and 500m where departures from in situ observations rarely exceed 1°C and 0.2psu. Exceptions concern some high variability regions like the Gulf Stream or the Eastern Tropical Pacific. Most departures from SST observations do not exceed the intrinsic error of the observations.

Ocean Monitoring and Forecasting in the European MyOcean GMES Marine Initiative

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The European Union GMES initiative has defined in 2005 the science and strategic Plan for the European "Marine Service" aiming at delivering short term forecasts and analyses/re-analyses for the assessment of the state of the oceans and seas, the safety of transport and the sustainable exploitation of ocean resources. MyOcean (2009-2012) and MyOcean2 (2012-2014) are a series of EU projects aiming at the practical implementation of the Marine Service approach in the global ocean and European Seas involving 60 partners in 29 countries. The products consider all the relevant essential climate variables, both from observational data and numerical ocean models at eddy permitting or resolving scales, and the service distributes openly and freely about 200 products of different resolution and quality. The Marine Service comprises the catalog, discovery and downloading of the products, the quality control protocols, the interfaces between observations and models, and a strategy for the research and development in the future years. Based on a pan-European organization, the full adding-value chain from satellite and in situ observations to downstream end-users applications is covered within the different application sectors of operational oceanography. The pan-European of this marine core, the main achivements of the first 3-year MyOcean project, dependence upon core observations that are altimeter data and Argo data, user statistics from the past 1,5 years of service activity, together with examples of user downstream services, will be described.

Oceanography – Mesoscale II

Topographic Waves in the Norwegian Sea observed with Satellite Altimetry

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Satellite altimetry measurements of sea surface height (SSH) in the Nordic seas reveal a region with distinctively high energy. This is the Lofoten Basin, located in the Norwegian Sea between about 2°W-10°E and 68°N-72°N over a topographic depression with a maximum depth of about 3250 m. The standard deviation of SSH over the observational period from October 1992 to July 2011 reaches nearly 15 cm in the center of the basin. Large part of the kinetic energy in the Lofoten Basin is contained in mesoscale signals with periods ranging from a few weeks to several months. A space-time lagged correlation analysis of SSH records is used to estimate the speed and direction of the maximum correlations as they propagate in space and time. The method reveals a cyclonic wavelike motion around the Lofoten Basin (linked to topography) with phase speeds of 2-4 km/day. The cyclonic wave propagation is also seen in time-distance diagrams, determined with Complex Empirical Orthogonal Functions analysis and wavenumber-frequency spectrum. Two major modes of propagating waves with wavelengths of about 500 km are determined with Complex Empirical Orthogonal Function (CEOF) analysis: a di-pole pattern and a quadri-pole pattern. The amplitude of waves associated with CEOF-1 and CEOF-2 varies from 1 to 8 cm and peaks over the deepest part in the center of the Lofoten Basin. The analysis of dispersion relation suggests that the observed propagating signals are related to baroclinic topographic waves.

On the Joint Use of High Resolution Tracer Images and Altimetric Data for the Control of Ocean Circulations

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Over the past two decades, altimetric satellites unprecedently observed turbulent features of ocean dynamics at the mesoscale. High resolution sensors of tracers such as the Sea Surface Temperature or the Ocean Color reveal even smaller structures at the submesoscale, which are not seen by altimetry. The role of the submesoscale in the ocean may be very important for the dynamic at larger scales. Therefore, we must benefit from the two types of observations (mesoscale dynamic and submesoscale tracer image) to refine the estimation of the ocean circulation.

The goal of this study is to explore the feasibility of using tracer information at the submesoscales to complement the control of ocean dynamic fields that emerge from altimeter data analysis at larger scales. To do so, an image data assimilation strategy is developed in which a cost-function is built that minimizes the misfits between image of submesoscale flow structure and tracer images. In the present work, we have chosen as an image of submesoscale flow structure the Finite-Size Lyapunov Exponents (FSLE). The choice of FSLE as a proxy for tracers is motivated by d'Ovidio et al (2004), where similar patterns between tracers and FSLE images are evidenced.

A prerequisite to the study is that the relation between the ocean dynamics and FSLE can be inverted, in other words that the submesoscale information transmitted through the intermediate FSLE proxy is effective in controlling the ocean system. This assumption has been successfully tested on several regional pieces of the ocean. Using a strategy similar to the one used in Data Assimilation, the sensitivity of FSLE horizontal patterns to velocity errors is investigated. To do so, a Gaussian velocity error field is created using fifteen years of altimetric data. A cost function is then defined to measure the misfit between the FSLE computed using velocities with errors and the FSLE derived from a 'true' (error free) velocity. It is found that a global minimum can be identified in the cost function proving that the inversion of FSLE is feasible. The next step is the inversion of submesoscale tracer information to correct a mesoscale altimetric field using real observation. The ocean dynamical variable to be corrected is the mesoscale altimetric velocity field using a high resolution tracer image. The strategy is similar to the one used to invert FSLE. The cost function measures the misfit between the FSLE derived from the altimetric velocity and the high resolution tracer image. Several test cases have been studied and demonstrating the success of the inversion of submesoscale tracer information to correct a mesoscale altimetric velocity field.

These results show the feasibility of assimilating tracer submesoscales into ocean models for the control of mesoscale dynamics and larger scales as deduced from altimetry and therefore the benefit of the joint use of tracer image and altimetric data for the control of ocean circulations.

Interannual Variability of the North Pacific Subtropical Countercurrent and its Associated Mesoscale Eddy Field

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Interannual changes in the mesoscale eddy field along the Subtropical Countercurrent (STCC) band of 18-25N in the western North Pacific Ocean are investigated with 20 years of satellite altimeter data. Enhanced eddy activities were observed in 1996-1998 and 2003-2008, whereas the eddy activities were below average in 1993-1995,1999-2002, and 2009-2011. Analysis of repeat hydrographic data along 137E reveals that the vertical shear between the surface eastward-flowing STCC and the subsurface westward-flowing North Equatorial Current (NEC) was larger in the eddy-rich years than in the eddy-weak years. By adopting a 2 and 1/2 layer reduced-gravity model, we show that the increased eddy kinetic energy level in 1996-1998 and 2003-2008 is due to enhanced baroclinic instability resulting from the larger vertical shear in the STCC-NEC's background flow. The cause for the STCC-NEC's interannually-varying vertical shear can be sought in the forcing by surface Ekman temperature gradient convergence within the STCC band. Rather than El Nino-Southern Oscillation signals as previously hypothesized, interannual changes in this Ekman forcing field, and hence the STCC-NEC's vertical shear, are more related to the negative Western Pacific index signals.

Beyond the superficial: Delving into the Deeper Currents around Madagascar

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Madagascar lies on the western side of the South Indian Ocean, acting as a barrier to the gentle westward circulation that would normally feed a major Western Boundary Current such as the Agulhas. In particular, the flow field to the south of Madagascar is complex, with deep eddies flowing through a region with shallow semi-permanent currents. This has made the determination of the mean difficult, with variability on scales ranging from weeks to years. Although there is now altimetric data spanning more than 20 years, not all questions can be addressed using those alone. This work synthesises the altimetric data with current records from a 14-month mooring deployment and regular XBT surveys from commercial vessels providing numerous temperature sections along the line from Réunion to Durban.

The current meters on the mooring strings reveal the very different mean flow at the surface and at intermediate depths, and show the broad-scale coherency as eddies pass through the region. Thus the flows inferred from visual and thermal imagery of near-surface waters are not indicative of the depth-integrated transport. By combining the XBT data with contemporaneous 2-D maps of sea surface height from altimetry, the typical vertical profile of an eddy in the Mozambique Basin can be discerned, indicating a uniform lift of isotherms in the depth range 400 to 880m (the maximum reliable depth on the XBT profiles). By subtracting the effect of eddies from the mean XBT section a clear northward current is revealed along the edge of the Madagascar Ridge.

Global Temporal Trends in Eddy Kinetic Energy from Satellite Altimetry

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Altimeter-derived geostrophic surface velocities are used to compute an 18 year time series of eddy kinetic energy (EKE) on a near-global 1/3 degree grid. The time series of global-mean and hemisphere-mean EKE show a strong seasonal cycle. Interannual variability is evident particularly in equatorial regions. A large peak in the near-global EKE time series is observed at the end of 1997 when the El Niño Southern Oscillation (ENSO) index was at 20 year high. However statistical analysis of the two time series shows a weak correlation suggesting that only the largest ENSO events can be distinguished from other sources of global EKE variability. Linear trends are best-fit to the 18-year time series and their statistical significance assessed using bootstrap techniques. The trend in the area-weighted, near-global-mean EKE is indistinguishable from zero and statistically insignificant. However, on a regional scale, statistically significant trends are found in all of the major ocean basins. Widespread negative trends occur primarily in both the Northern and Southern sub-tropical Pacific, with positive trends occurring in much of the North East Atlantic, the South Indian Ocean off Western Australia and in the Scotia Sea and Pacific-Antarctic Ridge regions of the Southern Ocean. In many locations the change in EKE during the 18 years is as much as 30% of the mean. For example, in the Subtropical Pacific, annual mean values have changed from 0.025 m^2s^{-2} in 1993 to 0.018 m^2s^{-2} in 2010. Whether these trends are the result of more frequent or more energetic localised eddy activity and the causes of these localised large (positive and negative) trends are discussed, including wind forcing and shifting ocean fronts.

The Future of Altimetry I

HY2 Data Quality Assessment and Cross-Calibration

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HY2 is the first altimeter satellite of China. The inclination of HY2 is 99.34 degree and orbit altitude is 971km. Since HY2 altimeter satellite launch, extensive validation of HY-2 data and cross-calibration relative to Jason2 have been performed. This paper presents the main results in terms of HY2 data quality: verification of data availability and validity, monitoring of the most relevant altimeter and radiometer parameters, assessment of the HY2 altimeter system performances. From global statistical analysis of HY2 GDR data, results for the altimeter measurement are derived in terms of bias and precision. It is demonstrated that the HY2 mission fulfills the requirements of high precision altimetry. In particular, it allows continuing the observation of the Mean Sea Level (MSL) variations at the same accuracy as Jason. In HY2's geodesy mission, after two years ocean monitoring mission repeated each 14 days, the repeated cycle will be 168 days as ERS1. The data in its geodesy mission will certainly perform a great contribution to global marine gravity field determination. Potential improvements and open issues are also identified, with the objective of still making progress in terms of altimeter data quality.

The SARAL/AltiKa Mission : a Ka-band Mission for Ocean Mesoscale Studies in 2012

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[1]CNES, FRANCE; [2]LEGI, FRANCE; [3]ISRO, INDIA

SARAL (Satellite for ARgos and ALtika) is a satellite mission dedicated to ocean environment monitoring, developed jointly by CNES and ISRO (Indian Space Research Organization), planned for launch in the second quarter of 2012. Its payload consists in an ARGOS instrument, and an altimetry payload including the AltiKa radiometer-altimeter. SARAL/AltiKa is intended as a gap filler mission between the RA-2 on-board ENVISAT (ESA, launched in 2002, now on a non-repetitive orbit) and the SRAL on-board GMES/Sentinel-3 (to be launched in 2014). As such, SARAL/AltiKa will fly on the same orbit as ENVISAT, allowing to re-use the mean surfaces fields in the data processing, and to have sea level anomaly monitoring with high quality from the start of the mission.

The AltiKa instrument consists in a Ka-band altimeter based on proven concepts and already developed subsystems, as it inherits a lot from Siral (European Space Agency CryoSat mission) and Poseidon-3 (on the JASON-2 mission), and an embedded dual frequency radiometer. As a result, the altimeter and the radiometer share the same antenna.

Contrary to past altimetric missions which were in Ku/C-band, AltiKa is a single frequency Ka-band altimeter, with an enhanced bandwidth. Indeed, the reduced ionosphere effects in Ka-band authorize a mono-frequency altimeter. Moreover, the enhanced bandwidth (480MHz w.r.t 320MHz for Poseidon3) induces a better vertical resolution. The spatial resolution is also improved, thanks to the Ka-band (smaller footprint) and the increased PRF (4KHz w.r.t. 2kHz for Poseidon3).

We present here the main characteristics of the mission, the expected performances, and the data access with their format.

The SARAL/AltiKa main scientific objectives concern various themes like meso-scale in open ocean, coastal areas, seasonal forecast and climate studies. Secondary objectives are the monitoring of continental water level and mean sea level variations, the observation of polar oceans, the wave and wind fields, the study of continental and sea ices, the access to low rain climatology, and the marine biogeochemistry.

So we also focus on the various scientific investigations in the frame of SARAL/AltiKa mission.

The Jason-3 Mission: The Transition of Ocean Altimetry from Research to Operations

Gerard Zaouche[3], Veronique Couderc[3], Francois Parisot[4], Parag Vaze[1], Walid Bannoura[2]

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The Jason-3 mission is planned as a follow-on mission to the Ocean Surface Topography Mission/Jason-2. The Jason-3 mission is planned to continue the reference satellite altimetry measurements for physical oceanography. However, an additional key long term vision of the founders of this measurement will come to reality, one of transitioning it from research to operational applications of this valuable measurement. Jason-3 builds upon the heritage of foundational and transitional missions such as SEASAT (1978), GEOSAT (1985), TOPEX/Poseidon (T/P, 1992), Jason-1 (2001) and OSTM/Jason-2 (2008) which have led to the understanding and development of a wide range of scientific and operational oceanographic applications of satellite altimetry.

The T/P and Jason-1 missions were developed by NASA and CNES and subsequently NOAA and EUMETSAT have taken on key partnership roles by providing mission operations services for the OSTM/Jason-2 project. For Jason-3, NOAA and EUMETSAT are the lead agencies with CNES and NASA as key partners providing system and mission development support.

The Jason-3 satellite is planned to operate in the same 1336Km, 66 Deg inclination reference orbit with essentially the same on-board instrumentation as OSTM/Jason-2. The instrument suite will consist of a 2 frequency Nadir Altimeter, Microwave Radiometer and three Precision Orbit Determination instruments (Global Positioning System - GPS, Doppler Orbitography and Radio-positioning Integrated by Satellite -DORIS, and Laser Retroreflector Array - LRA).

To fulfill the goals of moving satellite altimetry towards routine operations will require the close cooperation and coordination of international multi-agency mission managers, designers, engineers, scientists and operational systems developers. This paper presents the Jason-3 mission formulation and development plans and highlights the key aspects of making this multi-dimensional project move towards reality.

GMES Sentinel-3 and its Surface Topography Mission

Drinkwater, Mark[1]; Donlon, Craig[1]; Berrutti, Bruno[1]; Mecklenberg, S.[2]; Nieke, J.[1]; Rebhan, H.[1]; Klein, U.[1]; Buongiorno, A.[2]; Mavrocordatos, C.[1]; Frerick, J.[1]; Seitz, B.[1]; Goryl, P.[2]; Féménias, P.[2]; Stroede, J.[1]; Sciarra, R.[3]

[1]ESA/ESTEC, NETHERLANDS; [2]ESA/ESRIN, ITALY; [3]SERCO Italia SpA, ITALY

The Global Monitoring for Environment and Security (GMES) joint initiative of the European Commission (EC) and European Space Agency (ESA) marks the transition from R&D oriented efforts in Earth observation towards operational services through an autonomous and operational Earth observation capacity. The launch of the first Sentinel-3 satellite (i.e. S-3A) is planned in late 2013. Two S-3 satellites are currently in development, with the second (S-3B) expected to be launched approximately 18 months after the first. The currently planned GMES service duration of 20 years requires several satellites.

Key S-3 measurement requirements, corresponding to identified user needs, have been derived from GMES including:

- ☐ Sea surface topography (SSH), significant wave height (Hs) and surface wind speed to at least the accuracy of Envisat RA-2, with enhanced measurement capability particularly in the coastal zone, sea ice regions and over inland rivers and lakes;
- ☐ Global coverage Sea surface temperature (SST) at a spatial resolution of 1 km and equivalent accuracy to ENVISAT AATSR;
- ☐ Visible, and Short-Wave Infrared radiances for oceanic, inland and coastal waters at a spatial resolution of 0.3 km, equivalent to ENVISAT MERIS with complete ocean coverage in 2-3 days

GMES S-3 addresses these requirements by implementing and operating the following payload elements:

- ☐ Dual frequency (Ku- and C-band) Synthetic Aperture Radar Altimeter (SRAL) supported by a dual-frequency passive microwave radiometer (MWR) for wet-tropospheric correction, a Precise Orbit Determination package including a GPS receiver, and DORIS instrument and a laser retro-reflector;
- ☐ Ocean and Land Colour Imager (OLCI) delivering multi-channel, wide-swath optical measurements for ocean and land surfaces;
- ☐ Dual-view Sea and Land Surface Temperature Radiometer (SLSTR) delivering accurate surface ocean, land, and ice temperature.

A collaborative ground segment providing management of the mission, management, development, production and access to

core data products in an operational near real time delivery context.

This paper will provide a brief overview and status of the GMES S-3 mission, but will focus largely on the altimetry in relation to the goals of the surface topography mission. Out of the full list of core S-3 products, the altimeter product will include the classical surface elevation values both with Ku- and C-band measurements together with use of the echo waveform data from Level 1 for wave height and wind speed estimates. Different tracking algorithms will be used for specific surfaces like coastal regions, sea ice, ice sheets interior and inland water bodies. Altimetry products will be delivered as Near-Real-Time (< 3 hours after acquisition), with an orbit estimate from the GNSS and DORIS receiver. Meanwhile, Short Time Critical (< 24 hours after acquisition) and Non Time Critical altimetry products will be based on improved orbit estimates with complementary information from DORIS and the laser reflector. A summary description of S-3 altimetry data products and their anticipated performance will be provided.

GMES Sentinel-3 is a series of operational satellites that will guarantee access to an uninterrupted flow of robust global, collocated data products. Together with the other Sentinels, this mission will fulfil the monitoring needs of the GMES marine and land services and climate research communities. The improved design of its topography payload and the corresponding data products in particular will assure altimetry data continuity through the next decade.

From CryoSat-2 to Jason-CS

Francis, Richard [1]; Cullen, Robert [1]; Buechler, Kurt [1]; Parisot, Francois [2]; Coutin-Faye, Sophie [3]; Wilczynski, Peter [4]; Vaze , Parag [5]

[1]ESA/ESTEC, (NETHERLANDS);[2]EUMETSAT, (FRANCE);[3]CNES, (FRANCE); [4]NOAA, (UNITED STATES); [5]NASA/JPL, (UNITED STATES)

In April 2010 CryoSat-2 carried into Earth orbit the first radar altimeter using synthetic aperture principles, although similar techniques had been used on earlier missions to Venus. In addition to its SAR mode, CryoSat-2's radar has a second antenna and receive chain allowing precise interferometry. It is named SIRAL (SAR Interferometric Radar Altimeter) and its results have met all expectations, with handsome margins.

Even before the launch of CryoSat-2 the further development of this concept was underway with Sentinel-3. While its radar, SRAL (SAR Radar Altimeter) does not have the interferometer of CryoSat-2's SIRAL, it does have a second frequency, to enable measurement of the delay induced by the ionospheric electron content. Sentinel-3 will have a sun-synchronous orbit with latitudinal range up to 82º, compared to CryoSat's 88º.

SRAL will operate in the high-resolution SAR mode over coastal oceans and inland water, and revert to the classical pulse-width limited mode over the open oceans. For sizing purposes coastal oceans are defined as waters within 300 km of the continental shorelines. The SAR mode generates data at a high rate, so the major limiting factor is the on-board storage.

The next step in radar altimeter development is Jason-CS, which will provide Continuity of Service to the Jason operational oceanography missions. Jason-CS is primarily intended to provide overlap and continuity with Jason-3, and this extends to the partner agencies responsible (EUMETSAT, NOAA, CNES, NASA and now ESA) as well as to the technical aspects of the mission.

While maintaining continuity, Jason-CS will bring new features. Jason-CS has a strong heritage from CryoSat but will fly the traditional Jason orbit, which covers latitudes up to 66º from a high altitude of 1330 km. An new feature is the need to become compliant to the European Code of Conduct for Space Debris Mitigation, which requires removal of the satellite from the protected zone (between the Earth's surface and 2000 km altitude) within 25 years of the end of the mission. Perhaps of more importance to the end user, its radar, called Poseidon-4, is based on Sentinel-3's SRAL, retaining its dual frequencies and SAR capabilities, but adding further refinements.

The architecture of the radar is improved, with the extension of digital technology further into the domain of analog radio-frequency electronics. While this may be invisible to the scientific user, it will yield an instrument with higher quality and markedly superior stability.

More notably, an operating mode in which SAR and pulse-width limited mode are available simultaneously is under study. This would enable the benefits of SAR to be achieved over all ocean areas if the volume of data generated can be stored and downlinked. This only becomes tractable if some on-board processing can be introduced. The concept currently under study is reversible and enables operation over all the world's oceans.

SWOT: A High-Resolution Wide-Swath Altimetry Mission for Oceanography and Hydrology

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A new satellite mission called Surface Water and Ocean Topography (SWOT) has been developed jointly by the U.S.

National Aeronautics and Space Administration and France's Centre National d'Etudes Spatiales. SWOT will utilize the technique of radar interferometry for making wide-swath altimetric measurements of the elevation of surface water on land and the ocean's surface topography. The new measurements will provide information on the changing ocean currents that are key to the prediction of climate change, as well as the shifting fresh water resources resulting from the dynamic water cycle.

The noise level of conventional radar altimeters limits the along-track spatial resolution to 50-100 km over the oceans. The large spacing between the satellite ground tracks limits the resolution of two-dimensional gridded data to 200 km. Yet most of the kinetic energy of ocean circulation takes place at the scales unresolved by conventional altimetry. About 50% of the vertical transfer of heat and chemical properties of the ocean (e.g., dissolved CO_2 and nutrients) is accomplished by processes at these scales. SWOT observations will provide the critical new information at these scales for developing and testing ocean models that are designed for predicting future climate change.

While radar altimetry over surface waters has demonstrated the potential of this technique in land hydrology, a number of limitations exist. Raw radar altimetry echoes reflected from land surface are complex, with multiple peaks caused by multiple reflections from water, vegetation canopy and rough topography, resulting in much less valid data over land than over the ocean. Another major limitation is the large inter track distance preventing good coverage of rivers and other small water bodies. Yet one of the most threatening consequences of a warming climate is the shifting water resources. It is critical that we be able to monitor the global water levels on land for assessing the storage and discharge of lakes and rivers.

SWOT is based on the heritage of the Shuttle Radar Topography Mission (SRTM). Significant modifications of SRTM are required for a space mission with much higher accuracy and precision. A higher frequency at Ka band (~35 GHz) is chosen for the radar to achieve high precision with a much shorter inteferometry baseline of 10 m. Small near-nadir look angles (~ 4 degrees), required for minimizing elevation errors, limit the swath width to 120 km. An orbit with inclination of 78 degrees and 22 day repeat period was chosen for gapless coverage and good tidal aliasing properties. With this configuration, SWOT is expected to achieve 10 cm accuracy over an irregular vector land water mask grid with average node separation of 50 m. Other payloads of the mission include a Jason-class altimeter, a water-vapor radiometer, and a precision orbit determination system. SWOT is currently being planned for launch in 2019.

Plenary – Future Observational Requirements: Risks and Challenges

Argonautica, an educational Project using JASON Data

de Staerke, Danielle[1]; Bonnefond, Pascal[2]
[1]CNES, FRANCE; [2]GéoAzur, FRANCE

The Argonautica educational project makes actual oceanographic data available to primary and secondary students. This satellite data makes it possible to understand the oceans, their relation to environmental change and the effects on the living world. It is a chance for them to undertake a real investigation by taking part in a scientific projects that alerts them to the evolutions in society and make them aware of the major challenges facing humanity and what is needed to protect the planet.

The Argonautica project, in relation to various events and/or with help from scientific partners, proposes the following activities:

- monitoring of drifting buoys, some of which are made by the classes, or Argos beacon. This will enable the students to understand oceanic circulation, the links between ocean and environment (climate…) and how they vary, by comparing the data with that supplied by the JASON satellite.
- showing the impact of these variations on marine animals, by monitoring their migrations with Argos transmitters.

At the end of the school year, the students come together to report back on their work and two of the best projects have been chosen for a presentation in front of an assemblee of international scientists.

The Sea Level Climate record

Cazenave, Anny
LEGOS, (FR)

The Small Scale Processes - Sub-Mesoscale, Coastal and Marine Geoid

Fu, Lee-Lueng
JPL, (US)

Prediction of Inland Surface Water: The Contribution of Radar Altimetry

Peter Bauer-Gottwein
Department of Environmental Engineering, Technical University of Denmark, (DK)

Prediction of inland surface water dynamics remains an unresolved problem because of the inherent complexity of the land phase of the hydrological cycle. At the same time, reliable forecasts of floods and droughts over a range of spatial and temporal scales are becoming ever more important. Prediction of inland surface water dynamics relies on numerical hydrological models. Hydrological models have greatly benefitted from new observational data provided by past and ongoing earth observation missions.

This contribution reviews the use of radar altimetry to update and inform hydrological models over the past 20 years. Different strategies used to merge models and altimetric data are presented and discussed. Observational requirements for the different strategies are outlined and compared with the characteristics of past, present and future altimetric missions.

The Cryosphere

Remy, Frédérique
LEGOS, (FR)

Twenty years of altimetry has demonstrated that this sensor is a powerful tool for the observations of the sea ice and continental ice such as the Greenland and Antarctica ice sheets. For the later, the first clear contribution is the topography derived from the ERS-1 geodetic orbit (two 168-day cycles) for ice sheet dynamics study: it allowed us to discover subglacial lakes, subglacial hydrological networks or other features related to ice dynamics and to test and constrain ice flow models. Cryosat-2 (369-day repeat cycle) provides another useful geodetic mission but a denser mission is required in the future. The second important contribution was the measure of height changes thanks to the 35-day repeat orbit of ERS-1, ERS-2 and Envisat, that gave an unprecedented time and space resolution. The along-track processing of the data set gives the global height changes but also reveals large scale temporal variations due to changes in atmospheric forcing, the loss of mass and its impressive acceleration for several coastal glaciers, the emptying and filling of subglacial lakes, or the displacement of surface features. A major limitation is due to the varying penetration of the radar wave within the snowpack. The Envisat follow-on mission is SARAL a joint CNES-ISRO mission with the same repeat orbit but with the altimeter Altika acting on a higher radar frequency (Ka-band at 37 Ghz instead of the Ku-band at 13.6 GHz). The penetration error will be less important than for the previous altimeter but studies are needed to calibrate both series and ensure compatibility/continuity. The major requirement is the continuation of this repeat orbit for volume balance survey. Sea ice does not require an accurate spatial repetitivity and Cryosat-2 has shown its important contribution. The continuity of this kind of mission is required.

Operational Oceanograghy and Forecasting (Assimilation, Wind-Wave);

Dombrovsky, Eric
GODAE

The Role of the Altimetry Constellation

Parisot, François
Eumetsat

POSTER SESSION

Poster Session: Building the 20-Year Altimetric Record – Challenges and Achievements

Oceanography from Radar Altimetry - The Early Years

Hausman, Jessica[1]; Beckley, Brian[2]; Haines, Bruce[1]; Leben, Robert[3]
[1]Jet Propulsion Laboratory/Caltech, UNITED STATES; [2]SGT/NASA Goddard Space Flight Center, UNITED STATES; [3]CCAR/University of Colorado, Boulder, UNITED STATES

The ERS-1, TOPEX/Poseidon, ERS-2, Jason-1, Envisat and OSTM/Jason-2 satellites together have provided over 20 consecutive years of radar altimetry. Data from these unique observing platforms have helped redefine our understanding of ocean dynamics on global scales. These missions have ushered in an era of operational near real time monitoring of mesoscale circulations, as well as advanced our understanding of ENSO, wave heights and indicators of climate change, such as global mean sea level, ice cover, lake and river levels. Before these missions were conceived, earlier radar altimeters provided convincing evidence that the oceans could indeed be successfully measured from space. Skylab was launched in 1973, and carried an experimental radar altimeter system that provided the first indication that ocean topography could be measured from space. While it operated for only short passes, the Skylab altimeter was able to capture basic geoid variations, including a dip in the sea surface that corresponded with the Puerto Rico Trench. In 1975 GEOS-3 launched with the purpose of being a geodetic mission, but also showed that it was capable of measuring large mesoscale circulation features. Then, the first dedicated oceanographic satellite mission, Seasat, launched in 1978. It furthered the understanding of mesoscale features in the oceans and, despite its short life, cemented ideas of what were possible. The Navy GEOSAT mission further demonstrated that satellite altimeters could measure the oceans with increasing accuracy and precision. In 1985, GEOSAT's primary mission phase, the Geodetic Mission (GM), provided a dense network of global observations that would improve the determination of the Earth's gravitational field and sea floor topography. The secondary mission, GEOSAT Exact Repeat Mission, provided nearly three years of global observations along the Seasat 17-day repeat ground track. That enabled declassification of the GEOSAT altimetry data and the ability to analyze the collinear data by the scientific community to further study mesoscale features and ENSO, even though the primary GEOSAT GM geodetic data remained classified at the time. All of these missions showed that altimeters were very capable of measuring sea surface height and anomalies from space. Scientists were able to track eddies, improve bathymetric measurements, tide models and much more. They were also the proof of concept needed to get modern missions like TOPEX/Poseidon and Envisat off the ground. This presentation will highlight the major contributions of these early missions and describe how they paved the way for TOPEX/Poseidon, Jason-1 and other missions, allowing for over 35 years of radar altimetry and many more to come.

RADS: Consistent Multi-mission Products

Scharroo, Remko[1]; Leuliette, Eric[2]; Lillibridge, John[2]; Naeije, Marc[3]; Mitchum, Gary[4]; Byrne, Deirdre[5]
[1]Altimetrics LLC, UNITED STATES; [2]NOAA Lab. for Satellite Altimetry, UNITED STATES; [3]TU Delft/DEOS, NETHERLANDS; [4]University of South Florida, UNITED STATES;[5]NOAA/NESDIS/NODC, UNITED STATES

Although the principle of satellite radar altimetry is fairly simple, properly accounting for all the geophysical corrections across separate missions makes it complex to arrive at a homogenous dataset. To become a fundamental Climate Data Record (CDR) for sea level, mm-level signals need to be extracted from measurements taken from an altitude of 700-1400 km.

Data from nine altimeter missions are presently available in the Radar Altimeter Database System (RADS), forming the basis for a prototype Level 2 sea level CDR. The 20 years of "reference missions" (TOPEX/Poseidon, Jason-1, and Jason-2) are complemented by "mesoscale missions" (Geosat, GFO, ERS-1, ERS-2, and Envisat) and the "polar mission" CryoSat. The latter two groups increase the spatial coverage of sea level change and start yielding stability comparable to the reference missions through some recent developments in corrections, like orbits and ionospheric corrections.

RADS was first developed at the Delft University of Technology in the late 1990s in order to better compare and combine altimeter data from ERS-1, ERS-2 and TOPEX/Poseidon into a single database. At the time, limited resources required condensing the data to the most essential information such as sea level, wave height, wind speed and time and location of the measurement.

For the last ten years, development has continued at NOAA's Laboratory for Satellite Altimetry, while TU Delft has provided a web interface, an rsync server, and a mailing list server. About 43 institutes in 21 countries are mirroring part or all of the data set, while many others access the web site to make data requests on demand. Currently, RADS provides a multitude of additional variables needed to convert the original satellite range measurement into a climate-quality sea level record. RADS includes alternative variables to allow the user to assess the possible influence of model errors on sea level, and to correlate its variations with those in wind speed, wave height, and sea surface temperature.

More recent developments in RADS include:

- Fortran 95 code which allows easier expansion to new uses and parallelisation.
- Documented software library for users to build on to use the data set directly for their own applications, and share their code with other users.
- A number of convenient tools to analyse the Level 2 data set.
- Full documentation of all data fields contained in the data record.
- Improved attribute fields in the netCDF data files for CF-1.6 compliance and documentation.
- Web-based netCDF data selection.

We will demonstrate the high quality and consistence of the current data records, in terms of global as well as regional sea level variations and trends, and highlight the major error sources in the process, which are mostly secondary to the actual altimeter measurements.

SALP : Consistent Multi-missions Altimetry Products

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[1]CNES, FRANCE; [2]CLS, FRANCE

For almost 20 years, the French space agency (CNES) has been operating a multi-mission facility for managing, processing, validating and disseminating a wide range of altimetry products.

The Service d'Altimétrie et Localisation Précise (SALP) was developed with a consistent multi-mission strategy, and this baseline is still used when CNES is involved in new altimetry missions. In addition to DORIS receivers, SALP manages POSEIDON-class altimeters and it can perform routine production from telemetry to Level 4 products for several missions such as Jason-1, Jason-2, ENVISAT, Cryosat. SARAL/Altika and Jason-3 are the following in the list.

To fulfil its objectives, SALP is based on a large and robust ground segment (SSALTO - Segment Sol d'ALTimétrie et Orbitographie) which is carefully maintained and upgraded to follow state of the art recommendations from the Ocean Surface Topography Science Team (OSTST) community.

Thanks to this continuous effort, and to the active involvement of partner Agencies (NASA, NOAA, Eumetsat, ESA and soon ISRO), the CNES/AVISO portal is serving more than 3000 scientific user groups worldwide as well as operational oceanography services such as Mercator Océan and core services from the European GMES Program.

This paper describes the organization, the facilities and the resources involved in SALP. It emphasizes the benefits and synergies from using a consistent system for multiple altimetry satellites (past and present): the benefits range from cost reduction, to a better efficiency in terms of data quality, performance monitoring, and communication with the scientific community.

The REAPER project: Bringing ERS Altimetry data set to ENVISAT standards

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[1]ESA ESRIN, ITALY; [2]University College London, UNITED KINGDOM; [3]CLS, FRANCE; [4]isardSAT, SPAIN; [5]ESA ESOC, GERMANY; [6]Altimetrics LLC, UNITED STATES; [7]TUD-DEOS, NETHERLANDS; [8]GFZ Potsdam, GERMANY

ESA's first Remote Sensing Satellite: ERS-1 was launched on July 17, 1991 and operated until June 1996, completing one year of parallel operation (Tandem Mission) with ERS-2. Launched in April 1995, ERS-2 has operated for over 16 years with all instrumentation still working well despite the loss of the on-board tape recorders and the transition to gyro-less pointing. Since the launch of Envisat in March 2002, the continuing operation of ERS-2 has provided a valuable overlap of the Radar Altimeter missions. The existing ERS Altimetry data set is known to be not fully homogenous over the two-mission lifetime, as a result of different algorithmic evolutions performed on the ERS-1 and ERS-2 ground processing chains and of changes in the RA (Radar Altimeter) and MWR (MicroWave Radiometer) sensors behaviour due to ageing effects and on-board anomalies. The aim of the REAPER project is to reprocess all available ERS-1 and ERS-2 RA and MWR data, from July 1991 through to June 2003, to produce a coherent and homogeneous long-term series that is cross calibrated and offers continuity with the Envisat RA-2 (Ku & S-band bi-frequency Radar Altimeter) mission. The use of the latest geophysical models improves the corrections applied to the range measurement. By revisiting the instrument calibration algorithms and applying retrospectively the experience gained on the effects of instrument ageing, further improvements in measurement accuracy are gained. Derivation of a new Precise Orbit solution across the 12 year period results in a significant improvement to the orbit accuracy and hence the final surface height measurements. The resulting data set will allow greater exploitation than was previously possible of the full potential of the archived ERS Altimetry data set over ocean, land and ice surfaces. This paper describes the new processing algorithms and geophysical models that are used in the reprocessing chains, and the new products that will become available. We present estimates of the improvement in measurement accuracy achieved, and show the initial results of the cross-calibration of products between ERS-1 and ERS-2 and between ERS-2 and Envisat.

Geosat and GFO: Enhancements to two Historical Altimetric Data Sets

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Geosat, launched in 1985, and Geosat Follow-On, launched in 1998, provide unique altimetric data sets from a non-sun-synchronous 17.05 day repeat-period ground track. The final Geophysical Data Records (GDRs) from these two U.S. Navy missions have been the responsibility of NOAA's Laboratory for Satellite Altimetry.

In the intervening years the Geosat data have been enhanced several times, most notably with improved precision orbits and geophysical corrections. The original sensor data records and waveform data records have been recovered from 9-track tape for both the Geodetic and Exact Repeat Missions. The Geodetic Mission data have been merged and retracked, leading to major improvements in marine gravity and predicted ocean bathymetry. We are now embarking on merging and retracking the Exact Repeat Mission data, to complete the 4.5 year time series. There are ongoing efforts to extend the time series of global mean sea level by adding the Geosat measurements to those from the Topex/Jason and ERS/Envisat series of missions.

Geosat-Follow-On (GFO) suffered several hardware issues during its first two years, but ultimately provided GDRs from 2000 through 2008. New precision orbits for GFO, as well as Geosat, have been provided by NASA/GSFC based on ITRF2008 and other modeling improvements, but no full GDR reprocessing has yet been performed. The waveform data from this mission were acquired only on passes that traverse Greenland or Antarctica, but this resulted in good ascending pass coverage over Africa+Europe and descending pass coverage over North America. There is continued interest in retracking this limited set of GFO waveforms for continental hydrology studies, so we intend to produce a reprocessed GFO dataset that includes all available waveforms.

The status of the data sets from these two missions will be presented, along with a discussion of the ongoing enhancements and retracking efforts that are being made. The sampling characteristics of these missions, and the historical nature of the Geosat data from the late 1980's, continues to make them both valuable to the 25-year long altimetric data record.

Reprocessing TOPEX for the Climate Data Record

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TOPEX/POSEIDON as the first mission in the partnership between NASA and CNES in dedicated, high accuracy ocean altimetry missions forms a crucial part of the 20 year ocean climate record. TOPEX/POSEIDON used three altimeters over its lifetime: TOPEX (NASA) Alt-A and Alt-B and the experimental CNES POSEIDON, forerunner of the Jason series. The TOPEX altimeters had certain waveform features ("leakages") that have become increasingly important as altimetry is pushed to the sub-millimeter per year accuracy level. There was also the important transition from TOPEX Alt-A to Alt-B necessitated by changes in the point target response (PTR) of Alt-A, most clearly manifested by an apparent increase in significant wave height (SWH). An important difference between TOPEX and the CNES altimeters is that the TOPEX geophysical data records (GDRs) were produced by correcting onboard linearized estimates with parameterized algorithms on the ground, while CNES altimeters used waveform retracking.

In addition to these instrument processing differences many advances in orbits and ancillary data have been made over the years. In order to bring TOPEX data up to the standard of more recent altimeter data and to correct for waveform features and PTR changes the TOPEX data are being retracked with newly derived PTRs from calibration data and waveform adjustments ("weights") to correct for leakages. The basis for and progress on this work will be described. The plan for producing Climate Data Records consistent with the current Jason series data will be discussed.

The work reported here was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration with funding from the NOAA Climate Data Records program.

Reprocessing of The ERS Altimetry Missions - The REAPER Project

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ESA's first Remote Sensing Satellite: ERS-1, was launched on July 17, 1991 and operated until June 1996, completing one year of parallel operation (Tandem Mission) with ERS-2. Launched in April 1995, ERS-2 operated until July 2011 with all instrumentation still working well despite the loss of the on-board tape recorders and the transition to gyro-less pointing. After the launch of Envisat in March 2002, the continuing operation of ERS-2 provided a valuable overlap of the Radar Altimeter missions.

The existing ERS Altimetry data set (OPR and WAP products) is known to be not fully homogenous over the two-mission lifetime, as a result of different algorithmic evolutions performed on the ERS-1 and ERS-2 ground processing chains and of changes in the RA and MWR sensors behaviour due to ageing effects and on-board anomalies. The goal of the Reaper project is to reprocess all available ERS-1 and ERS-2 RA and MWR data, from July 1991 through to June 2003, to produce a coherent and homogeneous long-term series that is cross calibrated and offers continuity with the RA2 mission.

The use of the latest models will improve the geophysical corrections applied to the range measurement. By revisiting the instrument calibration algorithms and applying retrospectively the experience gained on the effects of instrument ageing further improvements in measurement accuracy are gained. Derivation of a new Precise Orbit solution across the 12 year period will result in a significant improvement to the orbit accuracy and hence the final surface height measurements. The resulting data set will allow greater exploitation of the full potential of the archived ERS Altimetry data set over ocean, land and ice surfaces, than previously possible.

This paper summarises the new processing algorithms and geophysical models that are implemented in the REAPER reprocessing chains, and discusses the improvement in the end-to-end measurement accuracy achieved. We present the initial results of the cross-calibration of products in the two tandem phases between ERS1 and ERS2 and between ERS2 and ENVISAT.

30 Years of CNES Programs in Satellite Altimetry

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We will present here the long term involvment of CNES in radar altimetry. CNES has been and is involved in most of the past current and future missions, both on the satellite systems, on the ground processing, as well as on related science and applications support. We will review here the different projects with a focus on those currently being developped; we will also highlight the quality, synergy and innovation that this sustained involvment has induced in this domain.

Envisat Altimeter System: Long Term Monitoring for Fast Delivery Data

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The IDEAS altimeter team (a consortium of specialized companies collecting engineering and scientific expertise over Europe) has been monitoring the performance and quality of the ESA ENVISAT Altimetry instruments and Fast Delivery (FD) products since 2003. The main tasks of this team include the routine data quality control of FD data, investigating and solving anomalies, advanced instrument performance assessment and instrument calibration.

For current altimeter missions, such as ENVISAT or CRYOSAT-2 satellites, specific performances are usually defined for consolidated data (such as GDR data), but similar objectives have not been defined for FD data.

Based on the long term monitoring of 10 year of FD ENVISAT Altimeter data, it is possible to define specific performance objectives for Near Real Time data for future altimeter missions. The aim of this study is to assess the actual ENVISAT Altimeter data performances and, from this, to define improved (and realistic) objectives for NRT data for future missions, by improving instrument performances and data processing.

DORIS/DIODE : Better than 3 cm On-Board Orbits for Near-real-time Altimetry

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One of the main challenges of the Jason-2 mission was to promote operational Near-Real-Time Altimetry. This activity had with Jason-2 to become fully operational. Considerable preparations have been made by the different project teams, towards meeting this goal with Jason-2.

In support of the Jason-2 goal, the DORIS system has evolved and accuracy specifications for the DIODE Navigation software have been refined since Jason-1 to better than 10 cm RMS in the Radial component as compared to the final Precise Orbit Ephemerides (POE) orbit. Note that this new requirement is more stringent than for final POE TOPEX/Poseidon orbit.

Two years (and an upload) after Jason-2 launch, the DIODE on-board orbits are indeed 3.3 cm Root Mean-Square (RMS) in the Radial component as compared to the final Precise Orbit Ephemerides (POE) orbit. Upload of a new version in the next months should drop this accuracy to 2.7 cm. Since the first day of Jason-2 cycle 1, the real-time DIODE orbits have been inserted in the altimetry fast delivery products (except a few hours around new version activation, in Feb 2010). Their accuracy and their 100% availability make them a key input to precise Near Real-Time Altimetry processings.

In parallel, other versions of DORIS-DIODE are flown on-bord CryoSat-2 (launched in April 2010) and AltiKa (to be launched this year). An overview of real-time orbit results on these three missions will be given and discussed in the presentation. On-board and ground products and their utility for the satellite systems will be commented also.

For the future, improvement of DIODE accuracy, driven by enhancement of the physical models, is still progressing. A one-centimeter consistency with ground POE orbits is possible with future versions, if analysis and model improvements continue to progress.

New Orbits of ERS-1, ERS-2, Envisat and TOPEX/Poseidon in the ITRF2008 Reference Frame and Their use for Mean Sea Level Research

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Precise orbits of altimetry satellites computed in the same reference frame using consistent models are a prerequisite for global and regional mean sea level monitoring, generation of mean sea surfaces, tidal model improvements and other applications. New precise orbits of the European Remote Sensing Satellites ERS-1 and ERS-2, Environmental Satellite (Envisat) and the National Aeronautics and Space Administration (NASA) and the French Space Agency Centre National d'Etudes Spatiales (CNES) Ocean Topography Experiment satellite TOPEX/Poseidon have been computed in the same for all satellites terrestrial reference frame (ITRF2008) using consistent models based mainly on the IERS Conventions (2010) within the Sea Level project of the European Space Agency (ESA) Climate Change Initiative. The orbits are derived using satellite laser ranging (SLR) and altimeter crossover data for ERS-1, additionally Precise Range And Range-rate Equipment (PRARE) measurements for ERS-2 and using SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) observations for Envisat and TOPEX/Poseidon. The orbit solutions cover the time spans August 1991 to July 1996 for ERS-1, May 1995 to July 2003 for ERS-2, April 2002 to December 2010 for Envisat and September 1992 to October 2005 for TOPEX/Poseidon. The paper describes the models and processing algorithms used for precise orbit determination and the results obtained. The quality of these new orbit solutions is presented in the comparison with the quality of the previous orbit solutions computed in the ITRF2000 within "Sea Level Variations - Prospects from the Past to the Present (SEAVAR)" project and in the ITRF2005 within the ESA project "Reprocessing of Altimeter Products for ERS (REAPER)" for ERS satellites and some external orbits for Envisat. The results of the orbit evaluation and examples of applications of the new orbit solutions for sea level investigations are given. We investigate also the influence of different terrestrial reference frame realizations used for altimetry satellite precise orbit determination on the mean sea level. For this purpose we computed precise orbits of these satellites at the time spans given above using three different realizations of the International Terrestrial Reference Frame (ITRF2000, ITRF2005 and ITRF2008), but the same consistent up-to-date models for all twelve cases. Since exactly the same models are being used, it is possible to study the influence of the different ITRF realizations on the sea level. In order to quantify the uncertainty in sea level trends connected to the choice of the ITRF realization, global and regional sea level trends are estimated for all twelve orbit solutions. In addition, global sea level trends are separately estimated for ascending and descending tracks for the evaluation of the different orbits.

Generating Precise and Homogeneous Orbits for ERS-1, ERS-2, Envisat, Cryosat-2, Jason-1 and Jason-2.

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Driven by the GMES (Global Monitoring for Environment and Security) and GGOS (Global Geodetic Observing System) initiatives the user community has a strong demand for high-quality altimetry products. In order to derive such high-quality altimetry products precise orbits for the altimetry satellites are needed. Satellite altimetry missions meanwhile span over more then two decades, in which our understanding of the Earth has increased significantly. As also the models used for orbit determination have improved, the satellite orbits of the altimetry satellites are not available in a uniform reference system. Homogeneously determined orbits referring to the same global reference system are, however, needed to improve our understanding of the Earth system.

The Navigation Support Office at ESA/ESOC provides precise orbits for ERS-1, ERS-2, Envisat and Cryosat-2. In 2008 ESA initiated the re-processing of the altimetry data of ERS-1, ERS-2 (REAPER) and Envisat, including the reprocessing of the orbit determination for these satellites. But also other altimetry satellites, as Jason-1 and Jason-2, would benefit from re-processing. The Navigation Support Office has with its NAPEOS software package the capability to process all three satellite geodetic tracking techniques (SLR, DORIS and GNSS). Therefore, we are in the unique position to do orbit determination by combining different types of data, and by using one single software system for different satellites, which matches the most recent improvements in orbit and observation modeling and IERS conventions. Thus we are able to generate a homogeneous set of precise orbits referring to the same reference frame for the various altimetry missions. Furthermore we are able to quickly re-process all solution allowing us to continuously upgrade the various solutions for all satellites.

This presentation focuses on the latest results from the re-processing efforts carried out by ESA/ESOC for the generation of precise and homogeneous orbits for ERS-1, ERS-2, Envisat, Cryosat-2, Jason-1, and Jason-2. For ERS-1 and ERS-2 SLR data are combined with altimeter data whereas for Envisat and Cryosat-2 DORIS and SLR data are combined, and for the Jason satellites GPS observations are used in addition to DORIS and SLR. We will present the orbit determination results and evaluate the orbit accuracy by comparing our orbits with external orbits generated by other analysis centers and will highlight some of the improvements obtained from our most recent upgrades.

Apparent Sea Level Variability and Trends Arising From the Choice of Orbit

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For every mission of the 20-year altimetric record several state of the art orbit solutions are available. This study aims at quantifying the error of local sea level variability and trends related to the actual choice of the orbit solution. We have started our analysis for the ERS-2 mission where we had an outstanding number of orbit solutions available. The focus has been on 7 different orbit solutions based on the same reference system and originating from three independent software packages and different orbit parametrizations. In order to investigate the temporal and spatial characteristics of the orbit related error, time series of radial orbit differences for each cycle have been calculated on a 1 by 1 degree grid for May 1995 to July 2003. Even though the global mean sea level trends are very close to each other the local trends differ by up to 1mm/year and seem to reflect drifts of the geocenters of one orbit solution relative to the other. Most differences contain annual components with amplitudes of up to 1.5 cm. The corresponding spatial patterns are again large scale and are related to shifts of the geocenter. Empirical orthogonal function (EOF) analysis shows that about 70% of the observed variability can be explained by motions between the geocenters of the analyzed orbits. A similar behaviour has been observed for the radial differences between two recent Topex and Jason-1 orbit solutions. Possible reasons for the observed orbit differences are discussed.

Multi-Mission Crossover Analysis: Merging 20 years of Altimeter Data into One Consistent Long-term Data Record

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The satellite altimeter scenario of the past two decades provides continuous and precise monitoring of the ocean surface with a beneficial spatio-temporal sampling. Since 1992 two or more contemporary missions are continuously available. For climate studies a consistent long-term data record is a fundamental requirement. However, combining missions with different sampling capabilities requires a careful preprocessing and calibration of all altimeter systems. A global multi-mission crossover analysis is able to connect the measurement from individual missions and merge them to one consistent long-term data record even if some of the missions are not operating on a repeat ground track. Upgrading and harmonization to the most up-to-date models and corrections is performed in advance. Then, we realize the cross-calibration by a least squares adjustment minimizing single- and dual-satellite crossover differences in all combinations as well as consecutive differences of the radial component of single satellites. Minimizing consecutive differences ensures a certain degree of smoothness of the radial component without introducing an analytical error function. This method provides time series of radial errors for the complete missions' lifetimes, the associated auto-covariance functions, relative range biases, systematic differences in the center-of-origin realization, as well as geographically correlated error pattern for all missions analyzed.

In this contribution we show results of a twenty years data record by cross-calibrating ERS1, Topex, ERS2, GFO, Jason1, Envisat, ICESat, Jason2, and CryoSat2. Special focus will be on the range biases of the different missions including their temporal behavior as well as on geographically correlated error patterns which map, if not corrected, directly to the sea surface.

Corsica: a Multi-mission Absolute Calibration Site

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In collaboration with the CNES and NASA oceanographic projects (T/P and Jason), the OCA developed a verification site in Corsica since 1996. CALibration/VALidation embraces a wide variety of activities, ranging from the interpretation of information from internal-calibration modes of the sensors to validation of the fully corrected estimates of the reflector heights using in situ data. Now, Corsica is, like the Harvest platform (NASA side), an operating calibration site able to support a continuous monitoring with a high level of accuracy: a 'point calibration' which yields instantaneous bias estimates with a 10-day repeatability of around 30 mm (standard deviation) and mean errors of 3-4 mm (standard error). For a 35-day repeatability (ERS, EnviSat), due to a smaller time series, the standard error is about the double (~7 mm).

In-situ calibration of altimetric height (SSH for ocean surfaces) is usually done at the vertical of a dedicated CAL/VAL site, by direct comparison of the altimetric data with in-situ data. Adding the GPS buoy sea level measurements to the “traditional” tide gauges ones, it offers the great opportunity to perform a cross control that is of importance to insure the required accuracy and stability. This configuration leads to handle the differences compare to the altimetric measurement system at the global scale: the Geographically Correlated Errors at regional (orbit, sea state bias, atmospheric corrections...) and local scales (geodetic systematic errors, land contamination for the instruments, e.g. the radiometer).

Our CAL/VAL activities are thus focused not only on the very important continuity between past, present and future missions but also on the reliability between offshore and coastal altimetric measurement. With the recent extension of the Corsica site (Capraia in 2004 and Ajaccio in 2005) and the ESA support, we are now able to perform absolute altimeter calibration for ERS -2, EnviSat, HY-2A and SARAL/Altika in a next future with the same standards and precision than for T/P and Jason missions. This will permit to improve the essential link between all these long time series of sea level observation.

Steep Bathymetry Changes in the Coastal Region South of Gavdos and their Relation to the Altimeter Bias of Jason-2

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The aim of this work has been to examine the relationship of steep bathymetry in the coastal areas around the permanent Cal/Val facility of Gavdos, and their influence on the produced calibration values for the Jason-2 satellite altimeter. Three reference surfaces have been chosen for this evaluation. These are (1) an improved but detailed geoid model, (2) a mean sea surface (MSS) model, as determined locally by using all available altimetric data in the region, and (3) several boat and GPS buoy campaigns, taken place along the satellite ground tracts south of Gavdos island. Details regarding the methodology applied for the determination of calibration values, as well as comparative results against all available reference models and surfaces will be provided.

This work outlines how the changes of steep bathymetry (from 200 m to 3500 m over 10 km) are reflected on the determined sea surface anomalies based on various reference surfaces for altimeter calibration.

Wet Tropospheric Correction for Exploitation of Altimetry Missions for Hydrology or Non-pure Ocean Surfaces: The Next Challenge

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The use of altimetry to determine the topography requires a reliable estimate of the wet tropospheric correction. The quality of this correction, derived from microwave radiometer data on board altimetry missions, is fully acceptable over homogeneous water surfaces, but there is still room for improvement for more complex surfaces such as coastal areas and ice surfaces. Moreover, new instruments will provide a more accurate range estimation and at an enhanced resolution (AltiKa, Cryosat, Jason-CS, Sentinel-3, and SWOT SAR interferometer altimeters). To fully exploit the potential of these new instruments for hydrology and ice topography, it will be necessary to develop dedicated wet tropospheric corrections.

The retrievals use, among other information, an estimate of the surface emissivity. In the case of sea surfaces, emissivity models have been exhaustively evaluated during the last 20 years leading to accurate and reliable retrieval algorithms (~1 cm rms error).

For slightly less than a decade, has increased the interest for coastal altimetry and thus for new approaches to get a reliable wet tropospheric correction. Whereas Fernandez et al. 2010, proposed to use GPS data to perfom the retrieval, in other studies the retrieval methods were adapted by using some decontamination protocols (Desportes et al. 2007) or by using the proportion of land in the inversion (Brown et al. 2009, Desportes et al. 2009). Combinations were also proposed (Fernandez et al, 2009, Mercier et al, 2007).

Over in-land waters and ice surfaces, the non-ocean part of the pixel strongly affects as well the measured TBs and remains an issue. On land or ice, the emissivity is close to one and varies in a complex manner in time and space, making it very challenging to model. Studies performed by Karbou et al (2006, 2010) have shown, for the first time ever, that it is possible to describe the land emissivity with an accuracy that meet Numerical Weather Prediction (NWP) requirements so that it is possible to use surface sensitive radiometer data. The emissivity is estimated within the NWP constrains and is dynamically updated to properly describe the surface.

Benefiting of a reliable estimate of the land emissivity opens new ways to exploit the radiometer measurements over non-ocean surfaces. It was the basis of the coastal retrieval method proposed by Desportes et al (2009), by including a pre-estimated value of land emissivity near the coast. As in NWP models, a variational inversion method was applied to get the optimal tropospheric correction. The challenge is now to develop similar methods for in-land water bodies (rivers, lakes) and for polar ice (ice cap, sea ice).

The objective of this presentation is to discuss the main issues related to wet tropospheric correction estimation for hydrology and ice altimetry studies, to present the very first results obtained over ice surfaces, and to highlight perspectives of this work for future missions processing.

Improving the Consistency in the Jason/TOPEX Microwave Radiometers Long-term Data Records Using Simultaneous Nadir Observations

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The microwave radiometers aboard the Jason/TOPEX satellites for altimetry missions are a key component of the system, providing important water vapor measurements for the major path delay corrections. Unfortunately, due to design constraints, the onboard calibration system is less than ideal, which introduces significant uncertainties in both the instrument calibration offset and gain determinations, and lead to on-orbit calibration errors that can propagate to the path delay estimates. This study improves the consistency in the Jason/TOPEX microwave radiometers long-term data records by using calibration references from the Advanced Microwave Sounding Unit (AMSU) on the NOAA and MetOp satellites from 1998 to 2012, as well as the Advanced Microwave Scanning Radiometer (AMSR-E) on the Aqua satellite from 2002 to 2011, using the Simultaneous Nadir Overpass (SNO) time series method. The effect of recalibration in the AMSU under the NOAA climate program will be taken into account. The CRTM radiative transfer model is used to account for the channel frequency and view-angle differences between satellites. After the calibration discrepancies in the Jason/TOPEX microwave radiometers are identified, a procedure for establishing consistency with AMSU and AMSR-E through correction coefficients is developed to ensure the long-term consistency and stability of the Jason/TOPEX Microwave Radiometer data records.

Trend and Variability of the Atmospheric Water Vapor: a Mean Sea Level Issue

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The ocean mean sea level is a key indicator of the global warming. Its long-term survey, thanks to altimetry missions, is an issue not only for climate understanding, but also for economic and social consequences of its elevation. The exploitation of altimetry measurements over Ocean relies on the feasibility to correct the altimeter range for different perturbations. One of them, the wet tropospheric correction is directly proportional to the integrated water vapor and is provided by a dedicated instrument, a microwave radiometer operating around the water vapor absorption line.

The uncertainty on this correction is today the main important part of the mean sea level error budget. Most of the past and current radiometers onboard altimetry missions experienced problems or drifts, which are hardly detectable due to the natural variability of water vapour (interannual variations, seasonal cycle, climate change). Methods to detect and evaluate these drifts are based on the long term survey of the measured brightness temperatures over stable targets (cold ocean or specific continental areas), on the comparison with measurements from other radiometers, or on the comparison with meteorological models (ECMWF, NCEP). These analyses show many inconsistencies and bring out the necessity to understand them.

In this context, the objective of this study is to compare the water vapor products from radiometers onboard altimetry missions with those provided by other instruments or meteorological analyses. The comparison of different estimations is tricky, because of inherent conception disparities: each mission has its own orbit, spatial and time resolution, processing and editing. Therefore methodological considerations to implement these comparisons are needed to avoid artifacts or biases in the results. The observed differences are analyzed in terms of intensity, spatial distribution, temporal trends and variability patterns, and characterized under different atmospheric and oceanographic conditions, to allow the detection of abnormal or irregular differences.

Calibration of Satellite Microwave Radiometers using GPS Reanalysis

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In this study we revisit microwave radiometer calibration using the latest GPS processing algorithms and models. GPS data from a network of global IGS sites is re-analysed using the IPSY-OASIS II software suite employing improved tropospheric modelling, absolute phase centre antenna calibrations and ITRF2008. The inclusion of this enhanced modelling has been demonstrated to improve tropospheric estimation. The GPS derived total zenith delay is corrected for the dry tropospheric component with the resultant wet tropospheric delay compared against the ENVISAT, Jason 1 and Jason 2 radiometric corrections. Anomalous behaviour will be referenced to the brightness temperatures at the corresponding frequency channels.

An Improved Objective Analysis Scheme of Scanning Radiometer Measurements to Compute the Water Vapor Path Delay for Altimetry

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Permanent gases in the atmosphere induce propagation delay to pulses emitted by satellite-borne radar altimeters to the ocean surface : the range measurement has to be corrected for this effect. The path delay due to water vapor (PD) varies from 1 cm in dry, cold air, to 40 cm in wet, hot air, and is highly variable in space and time. It has long been recognized that the most accurate way to measure it is to fly a microwave radiometer together with the radar altimeter, sensing the atmosphere at frequencies near the 22.235-GHz water vapor absorption line, along the altimeter path (i.e., nadir viewing). A second possibility is to compute the PD from meteorological models, but with poorer accuracy because such models often cannot map the atmospheric humidity short space and timescales. An alternate approach has recently been proposed by Stum et al. (IEEE Trans. Geosci. Remote Sens., 2011): it combines, through an objective analysis (OA) method, all existing scanning radiometer columnar water vapor observations, to derive the PD for any altimeter mission. This approach is motivated by the need to offer an improved PD correction for altimeter missions that do not embark a microwave radiometer, but also by the potential benefit to sea level rise studies using altimeter missions for which the long term stability of both the aboard radiometer PD and the meteorological model PD are uncertain. Improvements of the method will be presented, taking into account more sensors, refinements of the calculation of the statistical properties of the field of (sensor – ECMWF) PD anomalies to be analyzed, and of the sensor errors. More extensive validation results will also be shown, including statistical crossover analysis and spectral analysis. Its applicability to near real time altimeter processing (including Jason-2 and Cryosat-2) will be assessed.

Building a 20 Year Sea Level Record in the Arctic from Satellite Altimetry

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The Arctic Ocean is not covered by the oceanography prioritised TOPEX/Jason-1/Jason-2 altimeter missions normally used to study sea level change, as these satellites have been launched into an orbit with an inclination such that they only cover the regions within the 66 degree parallels. However the Arctic Ocean is of fundamental importance to climate. It contains e.g., more than 70,000 GTons of liquid freshwater, which if released could potentially disrupt the global thermohaline circulation and cool the climate of Northern Europe.

The only satellites covering the Arctic Ocean are the ERS-1/ERS-2/ENVISAT satellites (up to 82N), ICESat (86N) and recently Cryosat-2 (88N), but only the ERS-1/ERS-2/ENVISAT will offer decadal scale observations of sea level change in the Arctic Ocean.

The Arctic Ocean is notoriously covered with Sea ice which means that automatic retracking of the altimetric data in the region using the standard Brown model fitting method is close to impossible. One of the areas with less than 10 repeated altimetric observations over a period of 20 years, is the Beauford Gyre which controls the distribution of fresh water in the Arctic Ocean. Consequently, several attempts have been made to recover the sea level from radar altimetry in leads in the ice.

In this presentation we focus on retracking the ERS-2/ENVISAT time series using a highly advanced expert based system of multiple retrackers. This enables accurate ranging in both open sea surface and from all ice-covered regions within the 82° coverage of the ERS-2 and ENVISAT satellite.

This enhanced altimetric data record of up to 20 years in the Arctic Ocean is used to investigate sea level change and compare it with existing altimetric data sources in the region.

Monitoring of Arctic Sea Level with Multi-mission Satellite Radar Altimetry

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It has been widely accepted that the Arctic is particularly sensitive to climate variability. During the last two decades, significant sea-ice thinning increased discharge from Arctic rivers from permafrost degradation, and Greenland Ice-Sheet ablation has resulted in increased ocean freshening with changes in ocean transport and circulation, and sea-level. While TOPEX/POSEISON or Jason-1/-2 cannot observe the Arctic ocean beyond 66°N latitude, high-latitude observing radar altimetry missions (ERS-1/-2, GFO, and Envisat) have observed that the Pan Arctic sea-level, 1992-2010, is rising at a rate of 2.8±0.8 mm/yr, which is about two times larger than the observed sea-level rise at 1.9 mm/yr in the Russian Seas using long-term tide gauges (>50 years) over the last few decades. Altimeter measurements observe only seasonally ice-free oceans and there could be errors in satellite orbits causing potentially latitude-dependent vertical biases in polar sea-level measurements. In addition, tide gauges are located in regions susceptive to both solid Earth elastic loading as a result of rapid glacier/ice melt, subsidence due to permafrost degradation, and the effect of glacial isostatic adjustment, all of which add to the uncertainty of tide gauge estimated sea-level change. Previous studies available data sets use 1-Hz altimetry data covering only the ice-free Pan Arctic region, this contribution uses retracked altimetry with higher-sampling (10-20 Hz) over oceans with partial or seasonally sea-ice covers or with semi-permanent sea-ice covers, thus creating more altimetry coverage. The nominal EM Bias model used in previous studies to correct altimetry sea surface measurements is based on nonparametric model, which assume that the effect of the electromagnetic response over wave-scattered open-ocean, which is not necessarily the case in the sea-ice covered oceans. Ocean tide models used to correct altimeter measurements are likely having seasonal variability that is also not captured as only ice free observations were assimilated into most models. Here we study the feasibility of improving historic and current multi-mission (including CryoSat-2) altimetry data in the Arctic Ocean including radar waveform retracking of 10-20 Hz data to generate additional coverage, study the use of an alternative EMB model, and other improved corrections. Altimetry sea-level data will be validated against existing tide gauge data both in the seasonal/interannual and secular components. For the latter, we will use a variety of techniques including GIA modeling, GPS vertical velocities at tide gauge sites, and other vertical motion measurements, to validate the altimetry observed sea-level trends. The goal is to produce a long-term (up to two decades), accurate, consistent (with lower altitude observing satellite altimetry), validated satellite altimetry data record to study the contribution of Arctic Ocean to global sea-level rise under anthropogenic climate change

Recent Advances in the Development and Validation of a Sea Surface Height Climate Data Record from Multi-mission Altimeter Data

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The determination of the rate of change of mean sea level (MSL) has undeniable societal significance. The science value of satellite altimeter observations has grown dramatically over time as improved models and technologies have increased the value of data acquired on both past and present missions enabling credible MSL estimates. With the prospect of an observational time series extending into several decades from TOPEX/Poseidon through Jason-1 and the Ocean Surface Topography Mission (OSTM), and further in time with a future set of operational altimeters, researchers are pushing the bounds of current technology and modeling capability in order to monitor global and regional sea level rates at an accuracy of a few tenths of a mm/yr. GRACE data analysis suggests that the ice melt from Alaska alone contributes 0.3 mm/y to global sea level rise.

The measurement of MSL change from satellite altimetry requires an extreme stability of the altimeter measurement system since the signal being measured is at the level of a few mm/yr. This means that the orbit and reference frame within which the altimeter measurements are situated, and the associated altimeter corrections, must be stable and accurate enough to permit a robust MSL estimate. Foremost, orbit quality and consistency are critical not only to satellite altimeter measurement accuracy across one mission, but also for the seamless transition between missions (Beckley, et. al, 2005). The analysis of altimeter data for TOPEX/Poseidon, Jason-1, and OSTM requires that the orbits for all three missions be in a consistent reference frame, and calculated with the best possible standards to minimize error and maximize the data return from the time series, particularly with respect to the demanding application of measuring sea level trends.

In this presentation we describe the development and utility of the MEaSURE's TPJAOS V1.0 sea surface height Climate Data Record (http://podaac.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_ALL). We provide an assessment of recent improvements to the accuracy of the now 20-year sea surface height time series, describe continuing calibration/validation activities, and evaluate the subsequent impact on global and regional mean sea level estimates.

Gridded Altimetry - Revisited

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Many people prefer to use altimetry once the data from all available missions has been combined and mapped to a cartesian grid. The methods for doing this became relatively standard a decade ago but we decided it was time to re-evaluate the system employed in Australia. As well as taking advantage of the improved accuracy of the revised versions of the mission data (especially Envisat), we wished to compare the results of the traditional Optimal Interpolation approach with a much more sophisticated scheme developed as part of the Bluelink system for assimilation of many types of observations into a global hydrodynamic model. This system uses the output of a free-running model to determine the covariance matrix that has hitherto been described using simple isotropic analytic functions. Results of the new approach are compared with the traditional approach by comparison with a number of types of independent data: withheld altimeter data, Argo steric height, and velocities of drifting buoys.

Using Radar Altimetry, Combined with Bottom Pressure Data, to Measure Underwater Vertical Movements

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Subduction zones, when locked, have the potential of generating the most devastating events (earthquakes and tsunamis) on Earth. As subduction plate boundaries always lie underwater, measuring the deformation offshore is crucial for understanding the stress accumulation at these zones and thus for mitigating potential seismic risk. However, GNSS methods are not suitable as electro-magnetic waves do not penetrate underwater and alternative methods need to be used. Here, we combine altimetry and tide gauge data to obtain vertical deformation at two offshore sites in the New Hebrides subduction zone. The two sites, Sabine and Wusi Banks, are located on both sides of the tectonic plate boundary, respectively on the subducting Australian plate and the over-riding Vanuatu Arc. The 1999-2010 water depth series derived from seafloor pressure are combined with altimetry data to determine movements in a global reference frame. Sabine Bank pressure data combined with EnviSat data show that the deformation rate on the subducting plate is close to zero (-0.1 +/- 1.2 mm/yr) and Wusi Bank pressure data combined with Jason-1 and EnviSat data show that the over-riding plate is subsiding at this site at a rate of several mm/yr. This subsidence (downward motion) indicates that the subduction is locked and that stress is accumulating in the area. This study demonstrates for the first time that combined altimetry and pressure data can be used to derive absolute vertical motion offshore and thus bring new insights on processes occurring at subduction zones. . It also illustrates the usefulness of continuous long-term high accuracy radar altimetry records, even at local scale.

Evolution of Radar Altimeters Acquisition and Tracking Performances over the Years

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Thales Alenia Space, FRANCE

Radar altimeters are required to observe wide and heterogeneous areas, ranging from deep ocean to ice margins, passing over transitional coastal areas and in-land waters.

Over the past 20 years, from JASON mission to SENTINEL-3, and now with CFOSAT mission, ensuring data availability by increasing tracker robustness has been one of the main mission objectives in Thales Alenia Space.

The purpose of the paper is to give an overview of the evolution and the performance of the radar trackers designed so far and more particularly to focus on the two up-to-date trackers under development.

The characteristics of the conventional range discriminators from POSEIDON-2/JASON-1 and SIRAL/CRYOSAT mission and their adequacy regarding the surface type will be summarised.

The additional features used on POSEIDON-3/JASON-2, ALTIKA/SARAL and now through SRAL/SENTINEL-3 mission, allowing the tracking on specific areas (in-land waters in particular) will be discussed. The improvement consists in using a priori knowledge of the satellite height derived from a positioning system and a Digital Elevation Model stored on-board. This device allows the altimeter to focus on areas with irregular relief ensuring continuous data acquisition.

The development of the SWIM instrument (CFOSAT) provides a new range of observations thanks to the state of the art on-board radar signals filtering using real-time complete digital range compression. The instantaneous observable range window, that is about 60m on a standard altimeter using the deramp processing technique, is now extended to more than 4 km with the SWIM processing. Such a tracking window of 4 km-deep ensures a rich observability over complex areas.

These new radar trackers will allow a better observability over various and mixed areas improving thus the tracking capabilities over the years. The availably and quality of the data will be improved, and in line with the forthcoming altimetry missions.

Keywords: radar, instrument, acquisition, tracking, performance, ocean, land, ice, coastal areas, hydrology.

Monitoring Measurement Performance of the CryoSat SIRAL Level 2 Data Products

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University College London is an ESA-designated Expert Support Laboratory for the CryoSat instrument processing facility. We have validated and monitored performance for all three SIRAL measurement modes since the end of the commissioning phase in October 2010. A variety of tests and monitoring processes are performed on the GDR data on each 30-day cycle corresponding to the "data takes" in the mission planning. Results are continuously accumulated and form a growing time-line which now covers 26 cycles of data. Analysis of this data set allows monitoring of the long-term drift in the SIRAL sensor performance and in the end-to-end measurement performance.

We present here for the first time the results of monitoring 2 years of SIRAL Level 2 data products. This talk describes the monitoring processes applied, the anomalies they can detect and the performance metrics that can be observed to detect drifts. We also describe some of the lesser known features of the SIRAL data products. Emergent drifts in the global statistics are illustrated and discussed.

Consistency and Performance of CryoSat-2 LRM and SAR Mode Data over Open Ocean

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The ESA Earth Explorer mission CryoSat-2 provides a unique opportunity for exploring a broad variety of scientific applications in the fields of Geodesy and Oceanography. The consistency of all data and products used is an indispensable requirement for successful investigations and research. Unlike all other altimeter missions, CryoSat-2 GDR files consist of data derived from different measurement modes (LRM, SAR, and SARIn). As the majority of Altimetry data users presumably employ GDR data in their computations, focus will be set on the consistency and quality of this merged product. In this context a comprehensive analysis of the CryoSat-2 LRM and SAR Level 2 products available from ESA is carried out. The investigations will be done with respect to other altimeter missions (Jason-1/2 and Envisat) by means of a multi-mission crossover analysis. The quantification of the performance of CryoSat-2 SAR mode observations with respect to classical LRM mode observations is another question addressed in this contribution. The investigations carried out comprise the analysis of Level 1b and Level 2 data, including the application of dedicated SAR and LRM retracking routines in order to quantify the difference in performance.

SIRAL 2 on CryoSat 2 in Flight Operational Results

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Since April 2010 SIRAL 2, the radar altimeter, is producing state of the art science measurements with for the ESA CryoSat 2 mission. The paper will provide an overview of the instrument availability and its temporal characteristics since launch.

In particular we will provide an analysis of the operations of the three science modes (low, high resolution and the Interferometric mode) along with the variability of the time duration to acquire valid echoes as a function of the season.

The stability and accuracy of the data produced will be discussed through the data acquired and results from use of different calibration modes in flight: this means the instrument altitude and echo power restitution. In addition, we will focus on the interferometric behaviour regarding spacecraft environment evolution.

An overall budget including thermal behaviour of the electronic units and antennas, power consumption and radiation events observed since launch will be presented.

We demonstrate the behaviour of SIRAL2 on a monthly basis by processing millions of individual measurements. We conclude the instrument is highly stabile, within specification and will provide the highest quality measurements well beyond the lifetime of the mission depending on system and Agency resources.

Keywords: radar, in flight echo tracking, in flight calibration, interferometer behaviour and accuracy.

Sea Surface Height Determination In The Arctic Ocean From Cryosat2 SAR Data, The Impact Of Using Different Empirical Retrackers

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Cryosat2 level 1b data can be processed using different empirical retrackers to determine the sea surface heights and it variations in the Arctic Ocean. In the Arctic Ocean different retrackers (Threshold, Alpha, OCOG, Leading edge etc) will result in different sea surface height determination, as the echo power waveform is contaminated by superposition of reflections from various cryosphere features like sea ice, ice sheets, new frozen water, coasts etc. This makes waveform retracking in the Arctic Ocean considerably more difficult compared with the open ocean.

A retracker based on the combination of OCOG (Offset Centre of Gravity) method and Threshold method is used to develop the sea surface height in the Arctic Region. This retracker uses the statistical properties of the echo waveform to compute two difference thresholds (start and stop) for the neighboring power bins. Next, a loop is run to check the power differences throughout the waveform for neighboring bins. If this power difference is greater than the start threshold, the system records the beginning of a subwaveform. Further when the power difference of neighboring bins of this sub-waveform is less than the stop threshold, this is recorded as the end of the subwaveform. As a result the power waveform is divided into various subwaveforms each having one peak. The first subwaveform corresponds to the peak for the leading edge. Next, the OCOG method is used to determine the center of gravity of the first subwaveform. This provides the position of the leading edge and thereby the sea surface height is obtained. It is observed that applying the OCOG method on just the leading edge subwaveform results in improved sea surface determination as compared to its application on the complete waveform.

This sea surface height determination is to be compared with the Level2 sea surface height components available in the Cryosat2 data. Further a comparison is done with other known empirical retrackers such as OCOG, Threshold, Improved Threshold and â-parameter retracker.

7-Year Calibration of the Envisat RA-2 Altimeter Sigma Nought

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The Radar Altimeter 2 (RA-2) on board of ENVISAT satellite operates in two bands (S and Ku) and is primarily conceived to measure the range to the Earth surface. In addition to this primary objective, RA-2 is capable of measuring other parameters of the surface, and in particular the backscattering coefficient (sigma naught, σ^o) at nadir (zero degrees incidence angle). The calibration of sigma naught requires the exact knowledge of all the instrument and observation parameters that appear in the radar equation. During the on-ground testing, the RA-2 has been rather well characterized to ensure its performance in orbit, and this information is used in ground processing to invert the radar equation and to calculate the sigma naught. As the accuracy of some of these parameters may be not enough for the purpose of sigma naught calibration and/or they may change during the flight, a calibration strategy has to be implemented. In addition to an internal calibration loop, which does not include some subsystems (like the antenna), an external calibration can be performed by observing radar targets of a well know radar cross section or an extended surface of known sigma nought σ^o. As far as Ku band is concerned, the σ^o absolute calibration of the RA-2 has been performed using a reference target given by a transponder (TPD) that has been developed at ESTEC. This has been exploited during the 6 month Commissioning phase to generate early calibration results. In order to consolidate this calibration results and to monitor the RA-2 calibration of σ^o during the Envisat lifetime, a continuous monitoring was performed by operating the transponder as much as possible. Performing external calibration by the transponder requires operating RA-2 in the so called Preset Loop Output (PLO). During a preliminary phase (about 18 months) the transponder has been deployed in different sites along the satellite tracks (non-permanent sites). Four orbits have been selected, whose ground tracks were not far from ESRIN, Frascati (Italy). Subsequently to the non-permanent site phase, a permanent site has been considered for operating the transponder for the rest of the Envisat lifetime. This ensured acquisition of calibration data only each 35 days (the Envisat orbital cycle). The Department of Electronic Engineering (DIE) of Sapienza University of Rome has supported ESRIN to perform this activity, the first calibration campaign dating back to February 24th, 2004. The last campaign occurred on October 5th, 2010. Since then the change of the ENVISAT orbit hampered the prosecution of the activity. This paper aims to review the entire effort for calibrating the RA2 sigma nought measurements, which lasted for almost seven year. It will present the final outcome of the activity, providing the users with the correction (bias) to get the calibrated sigma naught and analysing its stability during almost the entire ENIVISAT lifetime.

Transponder Calibration of CryoSat-2 Datation, Range and Interferometric Phase Errors

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The CryoSat mission will determine fluctuations in the mass of the Earth's land and the marine ice fields. Its primary payload is a radar altimeter (named SIRAL: Synthetic aperture Interferometer Radar ALtimeter) that will operate in different modes optimised depending on the kind of surface [1].

Low-resolution mode (LRM) is a conventional, pulse-width limited altimeter. In SAR and SARin modes, transmitted Full Bit Rate (FBR) data consists of the individual, complex (I and Q) echoes. In SARin mode, there are two such echoes, one for each antenna of the interferometer. On ground, the radar echoes must first be synthetic aperture processed before incoherent multi-looking (in SARin mode also phase multi-looking is applied). This forms the Level 1b data. Data azimuth processed but right before the multi-looking is performed, are very convenient for calibration purposes as they still contain all the individual beam waveforms. These data are the stack data.

Transponders are commonly used to calibrate absolute range from conventional altimeter waveforms thanks to its characteristic point target radar reflection. ESA has deployed a transponder available for the CryoSat project deployed at the ESA Svalbard station.

We are using the ESA CryoSat transponder to calibrate SIRAL's range, datation, and interferometric baseline (or angle of arrival) to meet the missions requirements [2]. In these calibrations, we are using 2 different types of data: the raw FBR data (processed and analysed by ESTEC) and the stack beams before they are multi-looked (stack data) in the Level 1b (L1b) processor [3] (by isardSAT). The nominal operational L1b processing was modified for this study. The beam formation shall focus on a point target and the L1b location uses an algorithm to shift the nominal closest L1b position along the ground track to the minimum distance with the transponder.

Ideally the comparison between (a) the theoretical value provided by the well-known target, and (b) the measurement by the instrument to be calibrated; provides us with the error the instrument is introducing when performing its measurement [4]. The comparison is performed by fitting the theoretical model to the measurements provided in either the FBR or stack data. When this error can be assumed to be constant regardless the conditions, it will provide with the instrument bias, and when repeated over time, it can also provide with the instrument drift.

We will present the calibration results and conclusions over more than 2 years of CryoSar data.

Note: this abstract has also been submitted to IGARSS 2012.

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On the use of altimeter backscatter Measurements : versatile and multi-purpose Applications to address air-sea interaction Processes

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Over the last twenty years, the use of altimeter backscatter measurements helped to better understand the sensor physics as well as to advance on theoretical or empirical knowledges about geophysical parameters to better approach the sea surface statistical description (short wave spectrum, elevation, slopes and curvatures variances, ...) and/or to derive geophysical quantities (wind speed, air-sea gas transfer velocities, wave breaking, ...). Taking benefits from the potential to co-locate altimeter measurements with numerous and various sources of observations (in situ, model, satellite active or passive measurements, ...), a more consistent picture has emerged. This helps to refine the role of altimeter measurements as reference data to advance a generic and versatile consistent framework for synergistic studies where co-located model, in situ and other satellite sensor measurements (passive and active microwave, IR and optical) can be used to study in detail air-sea interaction processes.

Wind and Wave Climate of the Black Sea from Satellite Altimetry

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Operational satellite altimetry started in 1991 with the launch of the first European Remote Sensing (ERS) satellite ERS-1 by the European Space Agency (ESA) and soon after was followed by TOPEX/POSEIDON which was launched as a result of a French Space Agency (CNES) and the US National Space Agency (NASA). Since then, there is an interrupted stream of invaluable surface wind and ocean wave measurements covering a period of more than two decades from two series of satellites (ERS-1, ERS-2 and ENVISAT from one side and TOPEX/POSEIDON, Jason-1 and Jason-2 from the other side). Typically, this period may be considered sufficient for deriving various wind and wave climate information. However, there are two main difficulties. Although, those problems exist when dealing with global climate, they manifest themselves more distinctively in the case of the regional climate computations. The first problem is related to the nature of the satellite ground tracks that do not allow to sample the wind and wave conditions with relatively short time increments at any single location. Typically, the same location is re-visited by the same satellite every 10 days (for TOPEX/POSEIDON and Jason-1/2) or 35 days (for ERS-1/2 and Envisat). This can cause a problem if one is interested in regional wave climate as several storms can be easily missed in that specific region. The other difficulty is due to the fact that the measurements have been carried out by several missions with different characteristics. This later difficulty, can be overcome with a simple calibration exercise to bring all measurements to the same level. An absolute calibration is only possible if there are some in situ measurements to represent the ground truth. Thanks to the NATO TU-WAVES project, those measurements do exist in the Black Sea in the 1990's. Although the temporal coverage of the measurements is rather limited, the data set is an invaluable asset in the absence of other similar systematic measurements in the region.

The results from the calibration exercise in the Black Sea will be presented. Some results related to the wind and wave climate in the Black Sea will be provided and discussed.

New Measurement Possibilities from the Radar Altimeter: Retrieving the Variance of Ocean Wave Slopes

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A complete description of the physical state of the sea surface is important to support a full understanding of the changing atmospheric conditions and possible effects on air/sea interactions. For instance, the measurement of the significant wave height (SWH) by radar altimeter significantly improved our knowledge of the world's wave climate. An important subsequent step in the application of altimeter data was taken when a retrieval algorithm for estimation of wave period was developed.

The further development of retrieval algorithms may deal with estimation the variance of surface slopes, which is an important parameter for the description of the near-surface layer.

Unfortunately, the variance of slopes which effects the backscattering of microwave signal can not be measured by conventional wave-buoys and so albeit is not possible to analyze the correlation between backscattered radar cross section (RCS) and variance of large-scale slopes without additional research.

Therefore the first step in the development of a new retrieval algorithm is a measurement of the variance of large-scale slopes of sea waves by remote sensing methods. This is possible because the backscattering mechanism at small incidence angle is quasi-specular with reflection occurring from facets of wave profile oriented perpendicularly to the incident radiation. If we can measure RCS at a number of different incidence angles we can then determine the variance of large-scale slopes using well-known algorithms. Such measurements of RCS are provided by the Precipitation radar (PR) from the TRMM mission, which we have used to calculate the variance of sea slopes.

Processing of PR data allows the retrieval of slope variance and RCS at nadir probing. The completed analysis shown that correlation between RCS at nadir probing and variance of large-scale slopes is significantly higher than between RCS and wind speed. The dependence of variance of large-scale slopes from wind speed for fully developed wind waves was calculated and compared with formula of Cox and Munk.

In conclusion the first single-parameter algorithm for the estimation of the variance of large-scale slopes from altimeter data has been developed. The data processing confirmed the efficiency of the new retrieval algorithm.

Knowledge of the wave climate has been revolutionized by the advent of radar altimeter. For the first time we have a truly global picture of the variability of wave climate in time and space. At present, altimeter data are processed to provide estimates of ocean wind speed, significant wave height and wave period. Accurate estimates of the variance of large-scale slopes along track in every scattering cell and assimilation of this information in models will significantly improve our knowledge of air/sea interactions.

Which is the Best Approach for Altimeter Data?

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Altimeters have provided an unprecedented number of wind and wave data all over the oceans. Each one of the ones flying the sky samples the ocean surface many times a second, usually summarized into one datum per second, i.e. at 7 km interval. The quality of the data has been steadily improving in time. Although the number of data available may sound very large (each altimeter provides on average an order of 2 * 107 sea data points per year), once we focus on a certain area, both because of orbit period and data spatial density, the number of data becomes very low. Especially in areas where the storms are short-lived and possibly affecting a relatively restricted area, it is often disheartening to find an altimeter passing aside and/or before or after the storm.

This is a consequence of the general approach that has dominated the field in the last twenty years. Few, high quality (and expensive) altimeters. The question we want to raise is if, at least for certain purposes, it were not convenient to make available, together with the top level altimeters, a large number of smaller and cheaper altimeters. At the expense of top quality, but still well within the limits of most daily needs, this approach, properly planned, would provide a practically continuous cover of the whole ocean surface.

Present day wave climatology derived from satellite altimeter data rely, for each 100 x 100 km square, on only a few hundreds data per year. This data is not sufficient to derive a reliable climatology for the various areas, especially if these are characterized by a substantial variability from year to year. A clouds of satellites could easily increase the number to many thousands or more, a number larger than the standard yearly product of a wave measuring buoy, but at any location of the world oceans.

Validation of Wind and Wave Data of Reprocessed Altimetry Products

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ESA has been committed to reprocess its past and present Earth Observation Missions of ERS and ENVISAT using the latest available algorithms and applications to produce longer and rather homogeneous time histories. Some of the reprocessing campaigns have already concluded while some are still ongoing.

The full-mission reprocessing of the ENVISAT Altimetry Level 2 data set V2.1 has already completed. The data covering the period from 30 September 2002 (orbit 3061-cycle 10) to 19 September 2010 (orbit 44643 cycle 92) have been made available by ESA. The reprocessing campaign was performed using the IPF version 6.04 (L1b) and CMA processor version 9.3 (L2) and the CNES GDR-C precise orbit products. Similar campaign has been going on for the reprocessing of the ERS altimetry products (REAPER Project).

At the same time, ECMWF has been carrying out a re-analysis project called ERA-Interim in preparation for the ERA-CLIM which has just started. ERA-Interim aims also towards producing a long-term rather homogeneous model data set using the best available model and data assimilation techniques at the start of the project. The resolution of the ocean wave model used for ERA-Interim is rather coarse (1 degree or about 110 km). Two stand-alone wave model runs were carried out using ERA-Interim winds to generate the sea-state conditions.

The results of the validation of the wind and wave products from the reprocessed altimetry data sets (mainly the ENVISAT Altimetry Level 2 data set V2.1) against model wind fields from ERA-Interim and wave fields from the stand-alone wave model runs will be presented. Available in situ data will be used as well for the verification. The potential use of the reprocessed data set for the on-going ERA-CLIM will be also discussed.

Improving the Estimation of Significant Wave Height with Coastal-oriented Altimeter Products in the Gulf of Cadiz Coastal Area

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Research and development of altimetry in the coastal domain, a key region for the significant impact of changing oceans on society, economy, ecology and climate, is a challenging target for exploiting and enlarging the number of applications relying on satellite data. A thorough validation of the nearshore altimetry information is a key effort to ensure its success. The study presented here addresses the case of the continental shelf in the Gulf of Cadiz (SW Iberian Peninsula), a special environment of strategic social, economic and ecological importance. We have validated the significant wave height (SWH) derived from ENVISAT RA-2 signals at the highest possible along-track resolution (18 hz: 350 m) obtained from the COASTALT processor. Independent ground truth (in-situ) measurements have been used to check whether this new dataset performs nearshore as well as standard altimetry (where by 'standard' we mean 1 hz data with an along-track resolution of 7 km) in open ocean. The assessment of the new COASTALT SWH products is encouraging, showing a number of stable and precise wave height retrievals much closer to the coast than routinely achieved. In particular, at the boundary of 10-20km from land, low-noise averaged SWH values can be computed which in turn help to detect shorter-scale dynamical processes compared to the standard altimetric products.

Extensive Comparison of numerical Wave Model Results with Altimeter and SAR Wave Data

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Recent big swells cause coastal structure damages as well as accidental deaths on the East coast of Korea. They are often generated far offshore, on the center of the East Sea, and damage the coasts of Korea and Japan after travelling long distance. In order to prevent coastal damages and casualty from the sudden approach of big swells to the coast, accurate forecasting wind waves including swells with long period should be performed.

SWAN wave numerical model was executed to calculate wave information during the big swell event in February, 2008. Wave observation data are important to verify the wave information calculated from numerical wave model. However, most of wave data are from the coastal waters and no in-situ wave data are available on the center of the East Sea. In-situ offshore wave measurements are difficult because of high expense of instruments and high risk of operation.

Satellite wave measurements using altimeter make it possible to get wave information from the sea difficult to execute field measurements such as the center of the East Sea or exclusive territorial waters. This paper compares wave data calculated from the numerical model to the altimeter and SAR wave data as well as the buoy and wave gauges on the coastal waters. Also remotely sensed altimeter and SAR wave data themselves are compared with in-situ wave measurement data observed at Ieodo Ocean Research Station located in the Yellow Sea for validation of satellite wave data.

Foam Effects on Altimeter Response

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The effects of whitecaps foam on the backscattering of radio waves and therefore on the altimeter response were taken into consideration as early as 1983 (Zheng et al.), with further work by Gairola and Pandey (1985) . It is of course well known that foam and spray are essential in determining the dependence of wind response, especially for very high wind velocities; little or no effort however has been devoted so far to consider the effect of foam distribution over the sea surface on the wave-form shape and therefore on the Significant Wave Height and on the E/M bias of the Sea Surface Height. On the opposite, there are many recent results on the effect of foam emissivity on passive sensor, such as for instance Reul and Chapron(2003), Anguelova and Webster (2006). Recently there has been a revival of interest in this field (Gairola et al 2011); the poster will present some results of the altimeter waveform simulated by assuming a distribution model for the whitecaps, following classical work by Monaghan as well as recent results - among others - by Piazzola et al (2002) Within this framework, the trajectories of foam particles are simulated, from their birth (whitecap formation) through their decay. The connection between the thickness of the foam layer and the microwave is provided by reflectivity results by Zheng et al. as well as by Gairola et al. 1986, 2011). The procedure can highlight the formation of a bias on the estimated sea surface. Further work may help improve the understanding of both the altimeter biases and the whitecaps and foam movement mechanism.

On the Extreme Wave Climate Induced by Strong Northerly Winds in the Gulf of Mexico

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Altimeter data base obtained from Jason-1 satellite missions is used to study extreme wave heights in the Gulf of Mexico. A particular case is study when strong northerly winds were present. In situ data acquired by the NDBC buoy programme is also analyzed for the same period of time. While one of the goals is to describe the spatial distribution of significant wave height using along track altimeter information under the storm conditions in the Gulf of Mexico (GM), a methodology is also put forward to establish the optimal area of coincidence with the in-situ measurements. After a brief description of the satellite missions, the altimeter database and quality control procedures, a method for extracting only the information related to significant wave height from hurricanes (ESWH) is addressed. The data validation procedure is based on a series of comparisons between Hs measured with satellite data and those estimated from buoy measurements. The main results are based upon the method used to analyze coincident data, which takes into account the area of presence of waves of the typical period determined from the in situ buoy measured wave characteristics. A spatial description of the distribution of extreme waves climate in the Gulf of Mexico, is presented and the critical issue of the ability of the altimeter to properly detect high waves is also addressed.

Small Scale Storm Variability and Satellite Altimeter Data

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Altimeter data have been routinely assimilated and used to assess the reliability of wave forecasts for many years . A more recent application of such is to provide an indication of Small Scale Storm Variability due to the irregular wind structure at the sea level ("gustiness").

Such SSSV can be examined by making use of Jason-1 and ESA Envisat altimeter SWH data along passes in enclosed seas and by interpolating a trend in space for each passage. Statistical parameters such as standard deviation and autocorrelation of the oscillations around the trend are extracted and compared with similar statistics from state-of-the-art Meteo/Wave models. (Pugliese Carratelli et al., 2008 and 2012, Al Ragum et al., 2009). A variability has shown to exist on a scale as low as the resolution of altimeter data,. i.e. down to a few kilometres, while even the highest resolution models show a much smoother behaviour – probably due the inherent limitation of numerical techniques. Not all the signal behaviour is necessarily related to real variations of the wave height since the altimeter response is affected by many errors, especially in the vicinity of a coast: a discussion of such effects is reported in Goìmez-Enri et al. (2010); most of it, however, is certainly a measure of the oscillations of wave agitation, related to atmospheric instability (Abdalla and Cavaleri, 2002) The evaluation of wave climate for coastal and offshore works when no long records of wavemeter data are available, is generally based on the analysis of global and local weather and wave models , so the importance of SSSV cannot be overlooked; especially when dealing with archive data, which are normally computed on coarse grids and stored at a few hours intervals, research is needed to correlate statistical extremes to sampled data. The long history of altimeter wind and SWH data, acquired at intervals of a few kilometers, can be useful to this purpose.

The poster will present the latest development of this research activities: if available, tests will be carried out and shown for 20 Hz data, to evaluate the effects of higher spatial resolution, and for both Ku and C frequency to take into account the effects of rain and the influence of land or floating objects which may confuse the issue.

Airborne Lidar in Support of Ocean Topography Missions and Science

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With the growing interest in understanding air-sea interaction, upper ocean dynamics and thermodynamics, increasing emphasis has been placed on submesoscale ocean processes. Meanwhile the interest in coastal oceanography also requires both spatial and temporal resolution beyond the typical (ten-day) repeat cycle of satellite altimetry. As we move to higher spatial resolution, for example the 2 km requirement and 500 m goal of the Surface Water and Ocean Topography (SWOT) mission, the surface wave field will become of more significance both for the dynamics and for the sea-state bias corrections since the wave field correlates with the submesoscale dynamics through wave-current interaction. As the community moves into this regime of ocean dynamics, some of these needs can be met by the use of airborne lidar for the measurement of ocean topography from mesoscales of O(100) km to gravity-capillary waves of wavelengths O(1) cm. Thus airborne lidar can be used in the pre-launch and calibration/validation phases and to supplement the science goals of the mission. In this talk we present the results of airborne lidar measurements synchronized with Jason I altimeter tracks off the coast of California and in the Gulf of Mexico. We compare the airborne lidar measurements of the sea-surface topography and significant wave height (SWH) with Jason I data. In the Gulf of Mexico we also use coincident airborne hyperspectral and infrared imagery to characterize the gradients in sea surface topography and surface wave variables across the Loop Current boundary and eddies. The implications of the results for high resolution satellite altimetry are discussed.

30 Years of Altimeter Instruments Development and 20 Years of In-Orbit Heritage at Thales Alenia Space

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The first preliminary studies on the definition of radar altimeter for Sea Surface Height (SSH) measurements started in the 80's in Thales Alenia Space under CNES and ESA contracts. ESA decided to fly an altimeter on the European Remote Sensing Satellite (ERS1) and initiated the preliminary studies on this altimeter named RA(1). At that time, CNES contemplated the possibility of flying an ocean topography mission on its own. It was eventually decided to fly a NASA/CNES joint mission, Topex/Poseidon (T/P), embarking a US radar altimeter and a French experimental compact solid state altimeter named Poseidon(1). Since then, Thales Alenia Space is involved in altimeters design and manufacturing for more than 30 years. Thales Alenia Space developed almost all state of the art spaceborne altimeters for ocean, ice and land applications: RA1a (ERS-1), RA1b (ERS-2), Poseidon1 (Topex/Poseidon), Poseidon2 (Jason-1), RA2 (EnviSat), SIRAL (CryoSat), Poseidon3 (Jason-2), SIRAL2 (CryoSat-2), AltiKa (SARAL, to be launched soon), Sadko1 (GEOIK-2a), Sadko2 (GEOIK-2b, to be launched), SRAL1 (Sentinel-3a, to be launched), Poseidon3B (Jason-3, to be launched), SRAL2 (Sentinel-3b, to be launched), Sadko3 (GEOIK-2c, expected).

The present paper will present the characteristics, performances and technology evolutions lead through this unique 30-year heritage in radar altimeter instruments. Planned future evolutions will be also addressed and will conclude the presentation.

Poster Session: Coastal Altimetry

Towards Improved Coastal and Regional Products with Altimetry Data from Pistach Project

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Since 20 years, measurements delivered by altimetry have proven to be a powerful tool for our understanding of oceanic processes. All the improvements made in the knowledge of the open ocean dynamics have benefited from the altimetry constellation offered by several satellites flying together (at least two satellites with TOPEX-ERS and up to five satellites with currently JA1&2, ENVISAT, CryoSat-2 and HY-2 in orbits).

The scientific community now address the issue of coastal processes through modelization, in situ data and satellites measurements. Like for the deep ocean circulation monitoring, altimetry technique is one of the most promising solution. The impulse has started with the first Coastal Altimetry Workshop held in 2008 that gathered the scientific community to make a status and initiate a work plan on the altimetry data sets over coastal areas. Since then, the altimetry community has continuously worked to improve altimetry data sets in coastal zones.

The French Spatial Agency (CNES) is a major actor of this initiative and since 2008 delivers routinely Jason-2 PISTACH level 2 dedicated products for coastal applications.

Near the coasts, satellite altimeter data are limited by a growth of their error budget. This quality loss is due on one hand to the land contamination in the altimetric and the radiometric footprints until respectively 10km and 50km and on the other hand to inaccurate geophysical corrections (tides, high-frequency processes forced by atmospheric forcing, …).

In order to mitigate these limitations, the PISTACH products provide new retracking approaches, several state-of-the-art and higher resolution corrections in addition to standard fields.

The PISTACH effort was made for Jason-2 mission but the need for multi mission data sets (as it exists for open ocean) is regularly expressed by the scientific community through the different dedicated workshops. The need will become even more urgent with Cryosat-2 now available and AltiKa mission launched in the coming months.

This paper addresses the major achievements realised in the recent years to answer to the need for homogenised multi mission regional and coastal altimetry data sets (Level 3) with PISTACH project.

The New Guinea Coastal Current and Upwelling System: Seasonal Variability Inferred from Along-track Altimetry, Surface Temperature and Chlorophyll

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The New Guinea Coastal Current (NGCC) is part of the Low Latitude Western Boundary Current system of the South Pacific connecting subtropical to equatorial water masses. The variability of this narrow along-coast surface current is investigated using five Topex/Poseidon and Jason ascending tracks that are orthogonal to the coast. The cross-track geostrophic current is validated against an ADCP database and an ADCP mooring in the coastal current system. Relationship with the along-coast wind variability is examined and ocean color data (SeaWifs) and satellite SST (AVHRR) give information on the associated surface chlorophyll and SST patterns.

The NGCC forms a 80-150 km wide coherent vein from Vitiaz Strait to the northern New Guinea tip and varies mainly at annual periodicity. The maximum southeastward current anomaly occurs in February and reverses in austral winter with 8 to 18 cm s^{-1} amplitude. Current variations are correlated with the monsoonal wind reversal and are modulated by complex influences of equatorial and off-equatorial planetary waves

Combination of the SLA, SST and surface chlorophyll concentration allows for a description of the annual coastal upwelling system. While annual variability is dominant in the NGCC and surface chlorophyll signatures along the New Guinea coast, the main variability in SST is semi-annual. During austral winter (right panels), the NGCC flows northwestward, advecting cold water from the Salomon Sea along the coast. During austral summer (left panels), the coastal upwelling drives a negative SLA slope which in turn forces a southeastward NGCC. At that time, the upwelling can be detected by a cold water plume and a chlorophyll bloom. The upwelling starts in December, reaches its maximal expansion in February (around 200 km offshore the New Guinea coast) and finally disappears in April.

Using High Rate Altimeter Measurements for Coastal Studies: Example in the NW Mediterranean Sea.

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Appropriate data (re)processing and analysis allow the optimisation of the number of informations which can be derived from altimeter measurements. This is particularly true in the coastal zone where data are generally discarded due to problems with the altimeter radar echoes or to inaccurate corrections, but also because the standard processing is not tuned for ocean marginal regions. This results in a relatively large (10-40 km) data gap next to the coast in standard altimetric products. Even if this remains a very challenging exercise, several scientific groups work on extending satellite altimetric products into the shelf and coastal seas (COASTALT, PISTACH, CTOH, ...), by means of appropriate corrections and (re)processing of the data. This enhances data availability and accuracy close to land and then allows a better observation of the coastal oceans.

Here, the potential of full rate measurements will be analysed in the context of coastal studies in the Northwestern Mediterranean Sea. We compare Topex/Poseidon, Jason-I, Jason-II and Cryosat-2 performances, for both 1Hz and 20 Hz SLA data, using a dedicated data processing system, the X-TRACK software. This tool, developed and routinely operated at LEGOS by the CTOH group, has been specifically designed to provide greater availability of quality altimetry data in the coastal seas. The objective of this study is to analyse the actual resolution of different satellite altimetry missions for the observation of the coastal circulation. This will be done by investigating the consistency between altimetry and other observations (SST, tide gauge, ADCP currents). The NW Mediterranean Sea is an interesting case study because of the complex nature of its flow (short spatial and temporal wavelengths).

Coastal Sea Surface Height Monitoring by GPS mounted on a ferryboat

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Satellite altimeters have provided valuable sea surface height (SSH) observations in open oceans, but their use is limited in coastal region by many technical reasons, including signal contamination by lands and large complicated tides. Moreover, the temporal and spatial sampling intervals of the satellite altimeters are too coarse for smaller-scale coastal phenomena. In this study, complementary observations of the coastal SSH using GPS are examined.

Since August 2010, the SSH across the Tsushima Strait between Japan and Korea has been observed every 30 seconds using a real-time kinematic (RTK) GPS receiver mounted on a ferryboat "New Camellia" that serves daily round trips across the strait. The observed SSH includes high-frequency fluctuations whose amplitude reaches to a few meters in windy weather conditions. They would be caused by wind waves, and can be smoothed out by averaging over the ship route, although the averaging periods are required to be longer than approximately eight minutes as long-period waves aliased in the 30-second sampling intervals.

In winter, the cross-strait SSH profiles in daytime cruises agree well with those in night cruises, but they are significantly different in summer. Since the accuracy of the RTK GPS observations is known to decrease in daytime and in summer when activities of the troposphere and ionosphere are higher, we used the data in night cruises only for further analysis.

By removing tidal and geoid heights estimated by available local models, we determined the sea surface dynamic height (SSDH), which is compared with the dynamic height calculated from the 18-m depth de-tided velocity observed by acoustic Doppler current profiler (ADCP) mounted on the same ferryboat. Although patterns of both SSDT profiles, such as positions of peaks and slopes, agree in general, the root-mean-square (rms) difference remains a few decimetres. Excluding errors of tidal and geoid models by obtaining temporal variations of the monthly means, the similarity between two SSDT anomalies is improved as the reduced rms difference of several centimeters, which is significantly better than that between the ADCP SSDT anomaly and the along-track Jason-2 SSDT anomaly of the sub-satellite track in the Tsushima Strait.

Radar Altimetry for Monitoring of Marine and Inland Waters in Turkmenistan

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Satellite monitoring of water resources is of great importance for countries located in arid zones especially now when significant changes in global and regional climate are observed. In Central Asia, Turkmenistan is a country where 80% of territory is occupied by Karakum desert. Nevertheless, the southeastern part of the Caspian Sea, Kara-Bogaz-Gol Bay of the Caspian Sea, and the southern part of Sarykamysh Lake belong to Turkmenistan. The Altyn Asyr Lake will be an artificial lake 103 km long, 18.6 km wide and 69 m deep, which is under construction in Turkmenistan since 15 July 2009. The lake will appear in 10-15 years at the place of a natural Karashor Depression, which will be filled by drainage waters gathered from the irrigated lands of the country. Fortunately, altimetry tracks of TOPEX/Poseidon, Jason-1 and Jason-2 cross all the above mentioned water bodies, including the Karashor Depression. Information and software of the Integrated Satellite Altimetry Data Base (ISADB) developed at Geophysical Center of Russian Academy of Sciences were used for the processing and analysis of altimetry data for the southeastern part of the Caspian Sea, Kara-Bogaz-Gol Bay, and Sarykamysh Lake for 1993-2011 time period. We investigated seasonal and interannual variability of the above mentioned sea, bay and lake levels, as well as wind speed and wave height (derived from the altimetry data) in the Caspian Sea waters of Turkmenistan. Karashor Depression (still empty in spring 2012) and then the Altyn Asyr Lake (slowly filled by drainage waters in the nearest future) can be used as a test ground for the present and future satellite altimetry missions. As a first step, a digital elevation model of the depression was prepared basing on the data base of NASA Shuttle Radar Topography Mission (SRTM version 4.1) with 90 m spatial resolution.

New Features of the Tyrrhenian Sea Surface Circulation Emerging from the Analysis of the AVISO Dataset

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A detailed analysis of the AVISO altimeter dataset, for the period 1993-2010, gives new insights on the structure of the Tyrrhenian Sea (TYS) surface circulation and on its seasonal variability.

Both the maps of sea level anomaly (SLA) and those of absolute dynamic topography (ADT) show that from late autumn to spring the average surface circulation in the central and eastern TYS consists of a stream of Atlantic water that meanders around four large anticyclonic structures located along the Italian coast, while progressing cyclonically towards the northern part of the basin. Analysis of maps of the Okubo-Weiss parameter computed from the geostrophic flow associated to the SLA and of time series of the local SLA anomalies provides evidence that these structures are persistent anticyclonic vortices around which the winter-spring surface circulation organizes. The vortices appear to have cyclonic - even if less well defined - companions on the offshore side of the stream.

Overall, this indicates the existence of a coherent, basin-scale structure resulting from an instability of the Atlantic stream, whose evolution can be tracked in the SLA maps, showing that both the flow meanders and the anticyclones strengthen throughout the winter season. The picture is supported by the time series of the basin average of the eddy kinetic energy that displays recurrent minima at the end of winters, and by the calculation of the exchange term between eddy and mean energy, showing negative minima in correspondence to the four anticyclonic meanders.

Results are compared with the outputs of an operational model of the Tyrrhenian Sea circulation recently developed. The numerical evidence supports the description of the winter-spring circulation derived from the AVISO data, and provides further information on the seasonal variability.

Coastal Waveform Retracking for Sea Surface Height Estimates: A Fuzzy Expert System Approach

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It has been found that some waveform retrackers perform better than others at the coast. However, when evaluating retrackers it is difficult to determine which has performed the best and which should be used under various conditions. This paper selects the most appropriate retracker at the coast using a 'fuzzy expert system' approach. Waveforms were first retracked using different algorithms. The retracked results were then analysed using the fuzzy expert system. The system is defined by specific rules, which are used to evaluate the performance of each waveform retracker. The rules are defined based on statistical features of the retracking techniques. During the processing, the input retracked data were transformed into the fuzzy membership functions; and the complex nonlinear input-output relationships were defined. The fuzzy inference processed these fuzzy inputs to evaluate the performance of retrackers based on ranking values determined by the rules. This system, therefore, conveniently handles the uncertainty in the coastal retracking results. The retracked sea surface height (SSH) produced by the selected 'best-performing' retracker will be used as the output of the SSH profile.

Six cycles of 20-Hz waveform data from Jason-1 and Jason-2/ OSTM in the Great Barrier Reef, Australia, have been processed using this system to obtain the improved SSHs.

The results from this study show that the fuzzy expert system can be used to evaluate the performance of the waveform retrackers, and determine an optimal solution from an appropriate retracker. It is also found that the profiles of improved SSHs well agree with those of the geoid height based on the Earth Gravitational Model (EGM) 2008. By using the system, additional data near the coastline have been recovered up to ~4.5 km for Jason-1 and ~7 km for Jason-2 in the study area.

Use of Coastal Satellite Altimetry in an Operational Statistical Blending Method

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The combination satellite and tide gauge observations in a statistical model is useful for assessing storm surges in coastal areas (Madsen, HØyer and Tscherning, GRL, 2007). However, standard along-track altimetry products have limited quality closer than approximately 50 km from the coast, and are not available within approximately 10 km of the coast. Within the CoastAlt project, Envisat data from the coastal zone has now been processed, and these observations have been used to assess the improvements in the statistical model that combines tide gauge and satellite altimetry observations. The focus area for this study is the coastal zone sea level in the North Sea and the Baltic Sea.

The near-real time sea surface height information determined by the revised statistical model will be made operational within the ESA Esurge project, in preparation for data assimilation into the DMI hydrodynamic model for the North Sea - Baltic Sea area. The near-real time product will be presented and validated and the strategy for the data assimilation and impact assessment experiments will be presented.

Analyzing ENVISAT RA-2 Waveforms before and after the Costa Concordia Accident near Giglio Island (Northwestern Mediterranean)

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The retracking of radar waveforms is crucial in order to extend satellite altimetry information to the coastal zone, where particular targets (i.e. land, flat waters, ships) may act as signal contamination sources. On 13th of January 2012 the Costa Concordia cruise ship, with about 4200 passengers onboard, smashed its hull against the coast of Giglio Island, a tiny piece of land in the Tuscan Archipelago (Northwestern Mediterranean). Since then, the ship lies partly submerged in the water off the coast of the island. The dual-frequency radar altimeter (RA-2) on-board the ENVISAT satellite makes one descending pass (orbit 274) near Giglio Island, very close to the accident area (about 2Km), with a revisit time of 30 days. This particular condition represents a unique investigation opportunity, given by a steady and relatively large artificial target represented by the Concordia ship, being the orbit in the vicinity of a well-defined reflector, in addition to the pre-existing structure represented by the island. We propose here to analyze the physical and electromagnetic effects associated with this particular feature on the RA-2 waveforms, using a recently experimented tomographic technique (Scozzari et al., 2012). This activity can provide additional information for the interpretation of “bright targets” phenomena in the framework of a wider research activity aimed at the extraction of the geophysical information from radar altimetry signals in contaminated contexts.

Seasonal and Interannual Variability in Eastern and Western Boundary Currents: Connections to the Basin-Scale Circulation and Winds

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Using the nearly 20-year record of a long-track altimeter sea surface height (SSH) data, in combination with satellite and model estimates of surface temperature (SST), wind stress and phytoplankton pigment concentrations, we describe the interannual variability of the annual cycles of coastal currents and water properties in the Pacific Ocean Eastern Boundary Currents (EBCs) and the Western Boundary Currents (WBCs) in the Southwest Atlantic Ocean. The mid-latitude regions of the California and the Humboldt Current Systems (CCS and HCS) in the north and south Pacific are highly productive EBC upwelling systems, driven both by seasonal changes in regional wind stress and the distant influence of interannual (ENSO) and decadal (PDO) climate variability. The Brazil and Malvinas Current Systems (BCS and MCS) are strong WBCs next to broad shelves, driven by seasonal and interannual changes in the basin-scale wind stress curl. Rather than wind forcing, upwelling in the SW Atlantic is more strongly driven by the interaction of the WBCs and the shelf, resulting in a highly productive ecosystem along the shelf break. Closer to the coast over the broad shelf in the SW Atlantic, we expect strong tidal mixing and weaker coastal circulation patterns associated with wind forcing. Changes in the along-track SSH (SSH "deficits") on tracks crossing the shelf and coast are the result of changes in the density of the subsurface water, while changes in the slopes of SSH represent changes in local currents. By retrieving the along-track SSH closer to the coast than in previous studies (for both narrow and broad shelves), we are quantifying the relationship between the local coastal water mass properties, local winds and large-scale forcing by winds and currents. SST fields give us additional information on the water characteristics, while satellite-derived pigment concentrations extend the discussions to changes in the ecosystem productivity. Results from idealized and realistic numerical model simulations of the coastal circulation are used to examine the dynamics of the circulation in more detail.

The Use of Coastal Altimetry to Support Storm Surge Studies in Project eSurge

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One of the most promising applications of the new field of coastal altimetry is the study of storm surges. The understanding and realistic modelling of surges supports both preparation and mitigation activities and should bring enormous societal benefits, especially to some of the world's poorest countries (like Bangladesh). Earth Observation data have an important role to play, but the full uptake of these data by users (such as environmental agencies and tidal prediction centres) must first be encouraged by showcasing their usefulness, and then supported by providing easy access.

Having recognized the above needs, The European Space Agency has recently launched a Data User Element (DUE) project called eSurge. The main purposes of eSurge are a) to contribute to an integrated approach to storm surge, wave, sea-level and flood forecasting through Earth Observation, as part of a wider optimal strategy for building an improved forecast and early warning capability for coastal inundation; and b) to increase the use of the advanced capabilities of ESA and other satellite data for storm surge applications. The project is led by Logica UK, with NOC (UK), DMI (Denmark), CMRC (Ireland) and KNMI (Netherlands) as scientific partners.

A very important component of eSurge is the development, validation and provision of dedicated coastal altimetry products, which is the focus of the present contribution. Coastal altimetry has a prominent role to play as it measures the total water level envelope directly, and this is one of the key quantities required by storm surge applications and services. But it can also provide important information on the wave field in the coastal strip, which helps the development of more realistic wave models that in turn can be used to improve the forecast of wave setup and overtopping processes. We will present examples of how altimetry has captured a few significant surge events in European Seas, and we will describe how a multi-mission coastal altimetry processor is going to be integrated in the eSurge system. The delayed-time reprocessed coastal altimetry data will be blended with tide gauge data to extract the main modes of variability in the coastal regions. Then data from the tide gauges can be used to estimate water level in real time, based on the modes of variability found.

In a later phase of the project, the eSurge coastal altimetry processor will be extended to be able to ingest Near-Real-time (NRT) raw altimetric waveforms and generate the relevant NRT products, a definite first for coastal altimetry. The pilot regions for this application will be the European Seas (where an area of specific interest is the Northern Adriatic, which is being investigated within a related initiative called eSurge-Venice) and the North Indian Ocean.

In summary, we expect eSurge to be one of the first pre-operational applications of coastal altimetry and a proof of the benefits it can bring to society.

Monitoring the dynamics of the Agulhas Current using coastal Altimetry

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The Agulhas Current (AC) is the western boundary current of the South Indian Ocean. AC has a crucial role on ocean circulation and climate. Models and palaeoceanographic studies suggest that the Agulhas Current has a crucial role in ocean dynamics via its leakage, which transfers warm and salty water from the Indian Ocean into the Atlantic.

By better understanding the AC transport variability over the last 20 years and the dynamics of mesoscale variability such as Natal Pulses we will be able to address better its impact on global ocean circulation and climate studies.

The AC flows down the east coast of Africa following very closely the continental shelf. The continental shelf is very steep which makes the AC flowing most of the time very stably unlike other western boundary currents such as Gulf Stream and Kuroshio, which experience wide meandering features. Between the Delagoa Bay (at Maputo) in the north and Port Elizabeth city in the south, the continental shelf is very narrow and never exceeds 25km between the coast and the 200m isobath.

Recent work from various groups, e.g. Vignudelli et al (2005), Bouffard et al (2008) and others have shown that improved post-processing strategies can allow us to retrieve along-track Sea Level Anomalies (SLA) much closer to the coast than is currently available from standard regional, along-track altimetry products.

The purpose of this study is to explore the newly developed coastal altimetry data to reveal and understand better the Agulhas Current dynamics. In this paper we discuss the first results.

Coastally Trapped Waves Signals and Their Thermal Impacts : Synthesis of Results from Altimetry and Models

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We present a synthesis of a several-year investigation conducted with altimetry datasets on characterization and impacts of equatorial and coastally trapped waves in eastern Atlantic at fine temporal and spatial scales. It was first shown that fine scales of intra-seasonal coastal propagations were captured at first order by radar altimetry, despite the reputed poor quality of sea surface height anomaly reconstruction within the first fifty kilometers offshore. Hence the TOPEX-Poseidon dataset was first able to reveal, when properly filtered, an impressive continuous activity of long range SSHA propagations from the equator up to the two Atlantic extremities of Africa. As expected from several equatorial studies, coastal intra-seasonal propagations appear dominated by the arrival of first modes equatorial Kelvin waves, that follow the coast at speed estimates of 1.5 to 2.1 m/s at low latitudes, and almost infinite poleward of the coastal Angola and Senegal upwelling fronts. Amplitudes range from -5 to + 5cm, with also important along-track variations.

These characteristics were however subject to a certain level of suspicion, due to the near-coast breakdown of measurement quality, as well as tide-model uncertainties. NEMO OGCM 1/4° runs proved to reproduce with good accuracy most of these characteristics, opening therefore the way to thorough analyses of these signals and their impacts on SST. Interannual run and idealized experiments supported the altimetry results, and particularly the observed amplitude and velocity changes. Attribution of possible causes was therefore more robust and will be presented. SST impacts of up to 0.4°C/cm, suggested in observations by regression of SST on SSH along coastlines, are also supported by the model runs. The latest allow for a partition of advection and mixing processes at play, and uncover the competing or constructive mechanisms of upwelling and downwelling waves effects on the thermal stratification and the SST field.

Regional sea level anomaly Processing in the Gulf of Mexico

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Sea level anomaly from satellites and tidal gauges are combined to demonstrate the feasibility of regional sea level anomaly processing in the Gulf of Mexico region. Similar to the global sea level anomaly processing conducted by AVISO, the regional sea level processing including the following steps: 1) Quality control and editing of altimetry observation, 2) Repeat track analysis, 3) Filtering the noise, 4) Optimal interpolation to merge satellite data and tidal gauge data. Two innovative improvements are introduced in the regional sea level anomaly processing. First, the Hilbert-Huang Transform method is used to filter the noise in the along track data. The Hilbert-Huang Transform separates the original data into intrinsic modes based on the characteristics of the data. When only higher modes are combined to conduct filtering, the high-wave number noise is effectively removed. The data at coastal region can be retained for regional sea level anomaly processing. Second, the regional sea level anomaly processing makes use all the available observations instead of sub-sampling the along track data as practiced in the producing of the global AVISO product. It is demonstrated that without including the tidal gauge data, the regional sea level anomaly processing reduces the RMS (Root Mean Square) error of AVISO product by 10% in the coastal region by comparing with the independent 10-day low-pass filtered tidal gauge observations in the northern part of Gulf of Mexico. By including the tidal gauge data, the RMS error between the regional sea level product and tidal gauge observation is around 2-3cm, which is a significant improvement from 10-11cm of AVISO product. Further work is needed to assess the regional sea level product in the open ocean.

A Study on the Conformance of Altimetry and in-situ Sea Surface Data near coast in the German Bight

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Altimetry data near coast are validated in the German Bight using a network of tide gauge stations and GNSS stations maintained by the German Federal Institute of Hydrology (BfG) and by the Federal Agency of Cartography and Geodesy (BKG). The network consists of two measurement platforms off-shore and of other stations on islands and on the continent. All tide gauge stations are equipped with continuous GNSS. Some of the stations have additional instruments to measure sea waves and currents.

In cooperation with BfG, sea level observation measured by altimetry and tide gauges as well as significant wave height measured by altimetry and buoys are compared in the interval 2000-2010. The observed sea level is further compared to sea level computed by a regional operational model run by the German Federal Maritime and Hydrographic Agency (BSH).

For standard altimetry products the comparison of instantaneous 1-Hz measurement with tide gauge data shows a very good agreement. Interference from coast is almost absent for passes at the small isle of Helgoland, with distance of 8 km between altimetry and tide gauge. The correlation of 0.9 and standard deviation of 6-7 cm and absolute differences in observed heights of a few centimeters

(6.2/2.7/-0.4cm depending on the mission) confirm a very good agreement at off-shore locations.

The consistency is lower at the coast, due to disturbance of the signal as in Borkum with distance of 24 km between measurements. Reduced correlation and increased standard deviation (10.4 cm) and ellipsoidal height differences (31.1/29.3/25.3cm depending on the mission) are characteristic of coastal stations.

Due to different effects (ocean tide, wind, resonance) the differences between tide gauge and co-located altimetry sea level increases with their distance. This same reason explain differences between modelled and observed sea level. The GOT4.7 ocean tide model performs at best in the region, giving the highest correlation and smallest differences between altimetry and in-situ sea level (0.9 with ellipsoidal differences of 0.2 cm for Jason-2 in Helgoland).

With the PISTACH coastal product and our Envisat retracked data more data near coast are available for comparison at the coastal stations. Reduced correlation and increased standard deviation and ellipsoidal height differences are also in this case characteristic of most of the coastal stations.

We further plan to compare the sea level and significant wave heights derived from in-situ and model data to the sea level from the Cryosat SAR data and using the new GRACE- and GOCE-based geoid models models in order to estimate eventual biases occurring in SAR mode with respect Pulse-Limited (LRM) Mode and tune up the SAR re-tracking scheme.

Seasonal Sea Level Anomaly patterns over Argentine Continental Shelf

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Argentine Continental shelf circulation has been studied principally with numerical models. Results of these models have shown a mean northeastward flow south of 40ºS, e.g. Palma et. al. (2008). The seasonal pattern has been described also with in-situ data but only for a limited number of dates corresponding to oceanographic campaigns. Satellite data provide an opportunity to solve the spatial and temporal issue. In particular, the 20-year database of sea surface height collected by radar altimeters is a unique dataset to study the circulation in regions with low density of in-situ data. Altimetry over continental shelf and coastal regions has improved considerably in the last few years, allowing researchers to study these complex areas. The aim of this work is to study the shelf circulation with gridded altimetry data produced by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) and along-track altimetry data produced by CTOH (Centre de Topographie des Oceans et de l'Hydrosphere) over the Argentine Continental Shelf (30ºS-60ºS). Our first objective was to estimate the accuracy of the two data sets with in-situ data. Results show that error decreases (from 8 cm to 5.6 cm) for periods larger than 20 days. We then analyse the seasonal component of 18 years of SLA (sea level anomaly). The first 3 modes of variability explain more than 90% of the variance. Decomposition in Empirical Orthogonal Functions (EOF) of the seasonal cycle suggests that the first mode is related to the radiative cycle. The spatial pattern shows a meridional gradient between 35ºS and 45ºS and a zonal gradient north of Montevideo. These features cannot be explained by the radiative cycle. The second and the third mode explain only the 8.20 % and 1.34 % respectively, but do show a well-defined pattern which are discussed as a function of other variables.

Integrated Mapping of Coastal Sea Level Using Altimetry and Tide Gauges for Monitoring Extreme Sea Levels

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Sea level rise will continue over the 21st century and beyond. This will lead, along with possible changes in frequency and intensity of sereve storms, to more extreme sea level events and hence an increased likelihood of coastal flooding and erosion. This paper is to integrate data from multi-satellite altimetry missions (e.g., Topex, Jason-1 and Jason-2) and tide gauges into a consistent map of coastal sea level for monitoring of sea levels around Australia. Sea level observations are merged using a multivariate regression approach. The performance of the model is analysed through the investigation of the temporal correlation coefficient, hindcast skill and root mean square error between tide-gauge and altimeter observations. The technique was first applied in the south-east Australian coastal ocean. The results indicate that sea level change observed by altimetry is dominated by the Eastern Australian Current system. Near the eastern coast within about 60 km, sea level observations from altimetry and tide gauges are highly correlated. The investigation is then extended to other coastal areas around Australia. When considering the variability of coastal and oceanic sea level, Australia has several distinct regimes where sea level variability differs in the coastal and nearby deep ocean. Thus, sea level dynamic features are to be investigated, especially along the south eastern and northern Australian coastlines. The estimated sea level is also used to predict high frequency sea level variations during extreme sea level events, and is compared to in-situ observations. The results suggest that the multivariate regression approach can efficiently integrate the two types of sea level data in the study areas.

Poster Session: Cryosphere

CryoSat Cal/Val - Accuracy and Penetration Depth of the CryoSat SARIn product

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CryoSat-2 was launched in April 2010, as part of the European Space agency's (ESA) Earth Opportunity Programmes. The primary scientific objectives of the mission are to determine changes of the ice sheet elevation and sea ice thickness within its nominal lifetime of five years to get a better understanding of the short-term response of the Cryosphere to climate change. In order to validate the scientific data products four post-launch CryoSat Calibration/Validation Experiments (CryoVEx) were carried out since CryoSat-2's successful launch. The CryoVEx campaigns included co-coordinated field and airborne measurements at selected validation sites in the Arctic and Antarctica. We will present first results of CryoSat-2 comparisons with GPS data acquired at the Halvfarryggen ice dome in Dronning-Maud-Land (DML), Antarctica during CryoVExANT-2010. A second comparison will be shown with airborne laser scanner data acquired during the same campaign in the Blue Ice area next to Novo runway also situated in DML. The GPS and laser scanner data will be used as reference elevation for the analysis. For our comparisons, we use CryoSat-2 level 1b and level 2 data products acquired in the SARIn mode, since the validation sites are close to the coast with surface slopes of up to one degree. Both sites have different snow/firn properties, which can be used to determine the penetration depth of the Ku-Band signal. The area around Halvfarryggen is characterised by a strong east-west gradient in snow accumulation rate, ranging from 0.5 m to 3 m firn per year. The Novo area is pure Blue Ice, covered with small patches of snow. Therefore, different backscatter mechanism will dominate the received radar signal, volume scattering at the Halvfarryggen and surface scattering in the Blue Ice area, respectively. For volume scattering, the re-tracked surface elevation is typically biased with the effective penetration depth of the radar signal. In the Blue Ice area no signal penetration is expected and the re-tracked radar elevation should resemble the GPS determined surface elevation. Apart from results with respect to penetration depth, we will get a first estimate of the accuracy of the CryoSat-2 SARIn product using interferometric phase processing which accounts for across track slopes.

Initial Assessment of CryoSat-2 Performance over Land Ice

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Following the launch of CryoSat-2 in April 2010, we have examined the performance of the CryoSat-2 SAR Interferometer over the continental ice sheets of Antarctica and Greenland, the Artic Ocean, and, for the purposes of calibration, over the oceans. Our aim has been to provide confirmation of the engineering performance of the radar interferometer, and to provide an initial geophysical validation of the resulting elevation measurements. We have confirmed the engineering performance at system level of the interferometer through performing a sequence of satellite rolls over the oceans, which provide a surface of known behavior and surface gradient. The activity has identified some errors in the SARIN L1b data products presently issued by ESA. Once corrected, the ocean calibration has demonstrated that the interferometer measures across-track surface slopes with a precision of 25 micro-radians and an accuracy of 10 micro-radians, which may be compared with a pre-launch estimation of 100 micro-radians; in short, the engineering performance greatly its the specification. The elevation measurement over the ice sheets combines the interferometer measurement of across track slope with the range measurement deduced from the SAR echoes. We have examined the performance of the range estimation, and determined the range precision to be 19 cm RMS at 20 Hz. We have examined the retrieval of the phase information over the ice sheets, and found the phase estimates to be robust and little affected by the uncertain ice sheet topography. Based on the calibration of the interferometer, the contribution of the across track slope error is, at 0.4 mm, negligible. While the quantity of data available to us that contains the corrections identified by the interferometer is limited, we have been able to confirm the range precision values from a limited cross-over analysis. With the corrected data products, we are able to confirm that the system performance of CryoSat-2 will meet or exceed its specification over the continental and marine ice sheets. This presentation summarise the accuracy of CryoSat-2 observations, with a particular focus on the application of land ice. We also present a summary of scientific achievements from the first full year of observations.

Interferometric Radar Altimetry over Sea Ice Covered Regions

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CryoSat-2's payload, the SAR Interferometric Radar Altimeter (SIRAL) is the most advanced space-borne radar altimeter ever flown; the along-track resolution is reduced to ~300m though SAR processing and the inclusion of a second antenna allows for across-track interferometry. Although SIRAL's interferometric mode (SARIn mode) was designed primarily for use in coastal areas of the large ice sheets, a SARIn sea ice 'patch' was included in the CryoSat-2 acquisition mask to the north-west of the Canadian Archipelago so that the behaviour of SARIn mode over sea ice could be studied.

In conventional sea ice altimetry highly reflective openings in the ice cover - leads - are picked out and their elevation is taken to be the instantaneous sea surface height. The ice surface elevation is estimated using rough surface waveforms and then the two can be compared to infer sea ice freeboard and hence ice thickness. A problem this approach has is that scattering from off-nadir leads may dominate the power echo and, since the pulse propagates with a circular wave front, this introduces a height measurement error. The conventional pulse-limited altimeter cannot account for this error as it has no way of distinguishing the point of origin of power within a single footprint.

We demonstrate that using the across-track phase recorded in SIRAL's SARIn mode it is possible to infer the across-track direction of return of off-nadir leads, determine their location in the footprint and correct for the associated height error. This principle can be demonstrated using CryoSat-2 data along with Enivsat ASAR images acquired in March 2011. The sea surface height in the Arctic is then mapped with both SAR and SARIn mode in order to draw comparison between the two modes and their associated error budgets. Improvements in ice thickness retrieval using SARIn mode would suggest that SARIn mode can be used to cross-calibrate SAR mode acquisitions and could even replace SAR mode over the rest of the Arctic basin.

First Results of CryoSat-2 Observations of Pine Island Glacier

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Antarctica's ice sheets contain enough water to raise global sea levels by some 60 m, were they to be rapidly discharged. Satellite radar altimeters have monitored changes in the surface elevation of the Antarctic continent since 1992 and up to the present day. These data have permitted us to estimate that, overall, Antarctica is losing about 25 GT of ice per year, potentially contributing some 0.07 mm per year to the present rate of 3.0 mm per year global sea level rise. The greatest thinning has been observed to occur at the margins of the ice sheet, through accelerated drainage of glaciers into the ocean. Yet, due to the roughness and steepness of these fast-changing surfaces, these fast-changing areas have proven difficult to survey with conventional pulse-limited satellite radar altimetry. A striking example of rapid retreat and ice sheet thinning is the Pine Island Glacier, the central trunk of which has been observed to be losing volume at an accelerating rate, increasing from 2.6 ± 0.3 cubic kilometres per year in 1995 to 10.1 ± 0.3 cubic kilometres per year in 2006. Since the successful launch of CryoSat-2 in April, 2010, we have observed the ice sheet margins and glaciers with a nadir pointing interferometric SAR altimeter that has the capacity to measure steeply sloping terrain and, hence, increase the density of observations over these critical areas of the Antarctic ice sheet. In this paper we extend the time series of ice sheet elevation change observations at the Pine Island Glacier using the first full-year of calibrated CryoSat-2 data. Using these data, we demonstrate that CryoSat-2 is able to deliver a higher spatial density of observations, each of which exhibit higher accuracy in elevation retrieval, relative to past conventional pulse-limited altimeters. In addition, we provide an update on the current rate of thinning of the PIG.

Comparison of Sea Ice Freeboard Distributions from Aircraft Data and CryoSat-2

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Sea ice thickness on basin-scale is an important variable in the polar climate system, however datasets are sparse. The only remote sensing technique capable of obtaining sea ice thickness on that scale are satellite altimeter missions, such as the ICESat and CryoSat-2. The CryoSat-2 satellite was launched in 2010 and is equipped with the Ku-Band radar altimeter SIRAL. CryoSat-2 is part of the ESA's Living Planet Programme and was especially developed for the observation of changes in the cryosphere. This includes especially the determination of variations in sea ice thickness in the Arctic Ocean. For that purpose it is essential to validate the Cryosat-2 products. The CryoSat Validation Experiment (CryoVEx) combines field and airborne measurements in the Arctic and Antarctica in order to validate CryoSat measurements. Here we report the results from the first combined aircraft and satellite data acquisition over sea ice in the Arctic Ocean. The aircraft was equipped with ASIRAS, an airborne radar altimeter, which was built to simulate the SIRAL sensor on CryoSat-2. During the CryoVEx 2011/2012 campaign in the Lincoln Sea several Cryosat-2 underpasses were accomplished with two aircraft. One aircraft was equipped with ASIRAS and an airborne laser scanner; the second aircraft carried an electromagnetic induction device for direct sea ice thickness retrieval and an airborne laser scanner as well. Both aircraft flew in close formation at the same time of a CryoSat-2 overpass. This is a presentation about the results from comparing sea ice freeboard distribution of laser and radar altimeter measurements with the CryoSat-2 product within the multi-year sea ice region of the Lincoln Sea in spring, with respect to the penetration of the Ku-Band signal into the snow and the effect of surface roughness on the radar range retrieval.

CryoSat-2 Validation over Law Dome and the Totten Glacier in East Antarctica

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The TotCal / CryoVExANT2011 project is an Australian and German collaboration that contributes to the validation of the CryoSat-2 radar altimetry mission through investigations of a key portion of East Antarctica near the Australian Casey Station. The Totten Glacier is one of the highest flux outlet glaciers in East Antarctica with previous studies showing focused surface lowering (at rates > 1 m/yr) and mass loss across its highest velocity grounded region. The surface of the adjacent Law Dome has along and across-track slopes ranging from 0° to over 2°. Such slopes have been particularly challenging for classical radar altimeters, and the area is an excellent natural laboratory to test the performance of the advanced interferometric mode of the dual-antenna CryoSat-2 mission.

We seek to contribute to the validation of four aspects of the CryoSat mission through the use of in-situ static and kinematic GPS, aircraft LiDAR and ASIRAS radar altimetry, and in-situ firn measurements. The first component of the project provides independent estimates of the signal delay due to tropospheric water vapour using our network of six in-situ GPS sites deployed in each of the past two summer seasons (2010/11 and 2011/12). Second, we will assess the SAR-In mode of the SIRAL altimeter in an area of significant across-track slope through comparison with detailed topographic data collected using airborne scanning LiDAR and detailed snowmobile-based GPS surveys. The in-situ GPS sites deployed in the region also serve to provide reference stations for the precise positioning of the aircraft and skidoo trajectories. Third, we will assess potential spatial and temporal biases on elevation retrieval by CryoSat through comparison of the airborne ASIRAS radar altimeter data with the surface as determined by simultaneous scanning LiDAR observations. We further investigate spatial variations of radar return and near surface firn properties along a transect of firn pits and corner reflectors. Finally, we aim to compare CryoSat based estimates of elevation change over a range of regions (and surface elevation rates of change) with those determined from historic surveys, previous satellite altimeters results, and recent repeat airborne LiDAR surveys.

In this contribution we show initial results from processing of data collected over the 2011/12 field season, following the return of our GPS sites and related data in mid April 2012. We focus on the generation and accuracy assessment of the in situ Digital Terrain Model the covers our primary validation region on Law Dome. We present an assessment of the GPS derived aircraft trajectory of the AWI Polar-6 aircraft, as well as a comparison of surface topography derived via kinematic GPS and airborne LiDAR. Initial comparisons and assessment of the SAR-In returns over this region are provided.

CryoVEx 2011-12 Airborne Campaigns for CryoSat Validation

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After the successful launch of CryoSat-2 in April 2010, the first direct validation campaign of the satellite was carried out in the April-May 2011. Part of this was repeated in Spring 2012. DTU Space has been involved in ESA's CryoSat Validation Experiment (CryoVEx) with airborne activities since 2003. To validate the performance of the CryoSat-2 radar altimeter (SIRAL), the aircraft is equipped with an airborne version of the SIRAL altimeter (ASIRAS) together with a laser scanner. Of particular interest is to study the penetration depth of SIRAL into both land- and sea ice. This can be done by comparing the radar and laser measurements, as the laser reflects on the surface, and by overflights of laser reflectors.

The campaigns focused on five main validation sites: Devon ice cap (Canada), Austfonna ice cap (Svalbard), the EGIG line crossing the Greenland Ice Sheet, as well as the sea ice north of Alert and sea ice around Svalbard in the Fram Strait. Selected tracks were planned to match CryoSat-2 passes and a few of them were flown in formation flight with the Alfred Wegener Institute (AWI) Polar-5 carrying an EM-bird.

The paper presents an overview of the 2011-12 airborne campaigns together with first results of the CryoSat-2 underflights.

CryoSat Data Quality Overview

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CryoSat data are routinely controlled by ESA-ESRIN-SPPA office with various tools and with the support of the IDEAS industrial consortium. This presentation introduces to the structure of the data products, the available quality tools (Quality Checks and Monitoring Facility) and methodology, and shows the main statistical results from the data acquired since the end of the commissioning phase (January 2011). Due to some anomalies still present in the data, ESA is planning to operate a new version of the processors by March

2012, followed by a full reprocessing campaign in 2012. This presentation details the reprocessing schedule and the main improvements expected from the new release of the specialized processors at Level 1b and at Level 2.

Radar Penetration into snow on Arctic Sea Ice investigated during CryoVEx 2011

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Satellite radar altimeters such as SIRAL on CryoSat-2 can provide data on inter-annual trends in Arctic sea ice thickness. One key uncertainty associated with determining sea ice thickness using satellite radar altimetry is the penetration of the radar into snow cover on the sea ice. We present an investigation of radar penetration into snow during the first post-launch CryoSat Validation Experiment (CryoVEx) campaign in April 2011. At three field sites data were gathered around corner reflectors using ground and airborne radars; coincident field measurements were also made. One field site was located on the fast ice off the coast of Ellesmere Island, the other two were in the pack ice at 83.6 and 85.6 N. Additional data were obtained using airborne radars along a CryoSat-2 ground track. We present the experimental set-up, data analysis and penetration results, and discuss the implications for retrieval of sea ice thickness using satellite radar altimetry.

Present-Day Ice-Sheet Mass Balance Estimates

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Ice sheets are the largest fresh water reservoirs on Earth and along with mountain glaciers/ice caps, they comprise the dominant sources contributing to present-day sea-level rise under anthropogenic climate change. Radar altimetry in particular for high-latitude observing platforms such as ERS-1/2, Envisat and Cryosat-2, comprises an observational record of over 20 years for ice-sheet mass balance studies. Contemporary mass balance studies have largely relied on satellite and airborne data, including radar and laser altimetry, spaceborne gravimetry and synthetic aperture radar interferometry sensors. These measurement types are complementary and have respective advantages and disadvantages. Surface elevation measurements (airborne and spaceborne radar and laser altimetry and SAR/InSAR) have spatial resolutions from decimeters to several kilometers, temporal sampling of weeks to seasons/yearly, with the latter incapable of separating seasonal signals and trends, and requires knowledge of firn or ice density to infer ice thickness change from elevation change measurements. Surface elevation measurements have the advantage that they are much less affected by the subglacial topography motion, including those resulting from glacial isostatic adjustment (GIA) process, which is ~10% of the ice surface elevation change signal. Space gravimetry measurements from GRACE directly infers mass change at a spatial resolution at present no finer than 333 km (half-wavelength at the equator) and monthly sampling, however, are significantly affected by GIA in terms of gravity or mass change, and require exact knowledge of other information, such as atmosphere loading, to separate the mass balance signal from others. Contemporary estimates of the Antarctic and Greenland Ice-sheet mass balance and their corresponding contributions to present-day sea-level rise, depending on the data type and data spans, still have a wide range. Their estimates in units of equivalent sea-level rise, range from 0.07 to +0.71 mm/yr for Greenland, and from 0.29 to 0.79 mm/yr for Antarctica, respectively, indicating large discrepancies. Here we provide an updated estimate of the ice-sheet mass balance and its contribution to present-day sea-level rise, combining satellite altimetry, GRACE and other data, with improved constraints on the firn/ice density and GIA, which should enable the narrowing of the current discrepancies between the observed and geophysical causes contributing to present-day sea-level rise.

Sea-ice and Snow Facies Classification from Envisat Altimetry Data over the Polar Regions

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Two classification algorithms have been developed for Envisat altimetry mission. They take advantage of having both passive and active microwave sensors on the same platform with co-registered measurements.

The first one concerns a sea-ice flag algorithm that detects sea-ice corrupted sea surface height data within quality control processing for oceanography applications, but also provides sea-ice type (i.e. first-year ice, multi-year ice and wet ice) for cryosphere studies. Its performances have been evaluated based on collocations between the along-track Envisat data with reference maps built from combination of daily grids of sea ice concentration from SSM/I sensors and backscatter cross-section from SeaWinds scatterometer on QuikSCAT satellite. Results show good performances of the present approach for recognition of sea-ice corrupted data vs.

ice-free ocean data when compared to these combined SeaWinds and SSM/I records. Aspects such as: the continued reduction in extent of the sea-ice cover in the Arctic region, the decrease in the amount of multi-year ice, and changes in melt season duration, can be analyzed from the classification results.

The second algorithm aims to separate different snow regions within the polar ice sheets based on measured microwave signatures. Our approach broadens the description of the snow pack by taking into account characteristics such as surface roughness, grain size, stratification, and snow melt effects, whereas this latter has often been solely considered in most previous works. This difference in snow morphology is due to variable conditions in local climate which is governed by local topography. Such partition of the ice sheet might help to better understand relationships between microwave signatures and snow morphology and might represent a useful and simple tool for tracking the effects of climate change. These results come from the ESA WOOPI project.

Preliminary Results on Algorithm and Sensor Comparisons for the Estimation of Surface Elevation Changes over Ice Caps using Altimetry Data.

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This work presents the first results of a research activity aiming to compare estimates of ice cap surface elevation changes using different repeat altimetry algorithms and different sensors, in order to identify the best performing algorithm. This activity is part of the goals of the ESA Glaciers CCI project. The area chosen for this study is the Devon Ice Cap, which is a large ice cap on Devon Island in arctic Canada covering an area of 13700 km2. The algorithms selected are the dual cycle cross-over method and the repeat-track method. The first method is applied to Envisat radar altimetry data (RA-2) between 2002 and 2008, and the second method is applied to ICESAT/GLAS elevation data acquired during the period 2003-2009. The dual cycle cross-over method we apply to RA2 data has been shown to work well elsewhere, due to the relatively large volume of data and the independence from external datasets. In particular, this method does not require correction for slope induced errors, because the pulse-limited footprint is located at the same place on the surface, and so potential slope induced errors cancel and any difference between the two measurements reflects elevation change. For the GLAS data, the repeat-track method has been chosen due to the fact that the data are temporally more sparse. However, due to the relatively large spacing of the satellite ground track between repeat acquisitions, one of the major challenges in obtaining elevation change estimates is determining the local across-track slope. There are several methods to estimate the local topography between repeat-tracks, among which some do not require external data. However, for this preliminary study, a high precision digital elevation model (DEM) has been used to facilitate the along-track interpolation. We compare the absolute differences between the elevation change products obtained using the two different methods and sensors. In addition, we quantify the root mean square error, RMSE, and the correlation coefficient, R2, between the two datasets.

A Synthesis of 9 Years of Envisat Data over the Antarctic Ice Sheet, before Altika on SARAL, as a Follow-on 35-d Mission for Ice Sheet Survey.

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For 9 years, Envisat, a 35-d repeat orbit altimetric mission surveyed the Greenland and Antarctica ice sheet, providing an unique data set for ice sheet mass balance studies. Since November 2011, Envisat was transferred on a drifting orbit. The whole Envisat data set may now be processed along-track in order to provide height change with a good space resolution. Next summer, a joint CNES/ISRO mission, Altika on SARAL will be launched on the exact same orbit (more or less 1 km in the across track direction). This allows an extension of previous ESA missions. However, Altika operates in ka-band (36.8 GHz), a higher frequency than the classical ku-band (13.6 GHz), leading to important modifications of the interaction between radar wave and snow pack. In particular, the effect of temporal changes of the snowpack characteristics and the effect of the radar antenna polarization will be different, so that preliminary studies should be performed in order to be compared with previous observations.

We present in this paper a synthesis of all available information derived from Envisat mission for the scientific exploitation (mean and temporal derivative of the height, but also of the backscatter and of the two waveform parameters, snowpack changes corrections, antenna polarization correction, flag for the height temporal behavior) and for an optimization of the comparison with Altika (penetration depth estimated at icesat-envisat cross-over, and precise surface slope in both directions at the kilometer scale). These data should be available through Aviso as soon as possible after Saral launch.

Sensitivity of Observed Elevation to Backscatter Power of Satellite Radar Altimeter over the Antarctic and Greenland Ice Sheets

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Surface elevations derived from ERS1/2 and Envisat radar altimetry data show unrealistically large seasonal variations over Antarctica and Greenland which cannot be explained by snow accumulation and ice dynamics. Previous studies show that radar-altimeter-derived surface elevations over ice sheets are sensitive to temporal and geographical changes in the surface backscatter power, a likely indicator of radar penetration depth variation. Corrections have been applied to extract the real elevation change (dh/dt) from the altimetry-measured ranges (Wingham et al., 1998; Li et al., 2003; Davis and Ferguson, 2004; Zwally et al., 2005; Yi et al., 2011). In this study, we derive sensitivities between observed changes in elevation and changes in the backscatter power (AGC) using two methods (short-term and mixed term), which give similar sensitivities but have somewhat different correlation coefficients. We compare the two methods for correcting the dh/dt for the ERS and Envisat altimeters over Antarctica and Greenland. The resulting corrected h(t) series show significant differences from the observed h(t). In particular, the apparent seasonal cycle in the corrected h(t) is much smoother and smaller in amplitude. Also, in some locations the dh/dt derived from the corrected and uncorrected h(t) are quite different. The high correlation coefficient between observed surface elevation and AGC suggests that the observed large unrealistic short-term surface elevation variation is caused, at least partially, by backscatter power variation. This study confirms that an elevation backscatter correction is necessary for radar-altimeter-measured surface elevations. It is reasonable to assume that after the backscatter correction, the influence of backscatter variation on the long-term elevation trend will also be reduced and the trend in corrected elevation will represent a more realistic elevation change. Higher correlation coefficient and smaller amplitude of seasonal variation suggests that the short-term sensitivity might separate the backscatter power impacted elevation portion better than the mixed-term sensitivity.

Simulations of the Altimetric Signal Intensity Backscattered from 2D Layered Air/Snow/Sea-ice Rough Interfaces

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Remote monitoring of the sea-ice thickness is one of the main objectives of the Cryosat mission. On the one hand, sea-ice thickness is derived from the measure of the freeboard of the ice, based on isostasy and assuming that the density of water, ice, as well as snow, are known. On the other hand, even if the snow load is known, the penetration of the electromagnetic waves into the snow strongly depends on the electrical and geophysical characteristics of the snow layer (density, temperature, permittivity, roughness). The remote sensing of the snow layer thickness (SLT) remains a real challenge and will be useful to correct for the snow load for converting freeboard measurements from satellite altimetry into sea-ice thickness. If dual frequency radar altimetric data show a good potential for remote sensing of snow and more generally of penetrating media, (Legrésy et al., 2005), providing the SLT from Ku band data alone is highly motivated by the orbit of Cryosat designed to cover the entire Arctic.

A theoretical study, based on the 2D modelling of the scattering of electromagnetic waves by rough layered interfaces at normal incidence, has been carried out in order to investigate the capacity of snow penetration of Ku-band waves. The multi-layered model used in this study is based on the first-order small perturbation method (Afifi et al. 2010, 2012). Within its domain of validity, this approximate model allows a fast analysis of the multi-layered structures by means of analytical equations giving the scattered field and intensities. The total backscattered intensity IT is written as a sum of a coherent IC and a fluctuating IF contribution: IT = IC + IF

IC is the coherent contribution to the total intensity coming from the scattering of the stack of layers, and IF is the fluctuating contribution which takes into account the first order roughness effects.

The medium is considered as a stack of three layers, with two interfaces, air/snow and snow/ice.

Several simulations have been conducted by varying the temperature, permittivity, roughness and thickness of each layer and the results are presented. More specifically, the influence of the snow thickness on the backscattering is analysed.

References: Afifi S., Dusséaux R., de Oliveira R., "Statistical distribution of the field scattered by rough layered interfaces: formulae derived from the small perturbation method", Waves in Random and Complex Media, Vol. 20, No. 1, 2010, 1-22 Afifi S., Dusséaux R., << On the co-polarized scattered intensity ratio of rough surfaces : the probability law derived from the small perturbation method >>, IEEE trans. On antennas and propagation, 2012, in press Legresy B., F. Papa, F. Rémy, G. Vinay, M. Van den Bosch and O.Z. Zanife 2005. ENVISAT Radar Altimeter measurements over continental surfaces and ice caps using the Ice2 retracking algorithm. Remote Sensing of the Environment. 95. 150-163.

Distribution of Small Icebergs in the Southern Ocean based on Altimetric Waveforms Analysis and SAR images

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Icebergs are conspicuous features of Southern Ocean and their possible role in the climate issues has been recently explored. For example, it is now clear that Antarctic icebergs are important to the marine ecosystems, to the carbon budget and to deep water circulation. Although there is good understanding regarding iceberg formation (i.e.,calving of ice shelves, glacier tongues or ice cliffs), the interannual variability or the effect of extreme events in their formation, like the collapse of large ice shelves (e.g. Larsen-B in 2002), are still not completely clear. The collapse of Larsen-B resulted in a large amount of small icebergs that spread throughout the Weddell Sea. In spite of their size, the contribution of small icebergs to meltwater injection can be equal or greater than the input by large icebergs. However, the logistical difficulties during the winter months and the absence of commercial routes in the Antarctic region result in a lack of observational data on Southern Ocean small icebergs. In that sense, it has been recently determined that radar altimetry waveforms (20 Hz) products can be used to identify targets like small icebergs (areas >1 km^2). This allows observations of those iceberg fields for the entire Southern Ocean (north of 65ºS) spanning almost 20 years. This work presents preliminary results of icebergs distribution patterns based on waveforms analysis, emphasizing on extreme events such as the Larsen-B collapse. The dataset is based on waveforms from JASON-1 and 2 Geophysical Data Records (GDR) products and also uses Synthetic Aperture Radar images (SAR). The latter is used to visually identify selected icebergs. The advantage of using the altimetry waveform dataset is the low computational cost when compared with SAR images as well as the longer temporal coverage (1992 until present). The main limitations are that (i) altimetry data is only available to the north of 65ºS and (ii) it is necessary to validate waveforms observed as icebergs. The analysis of waveform data showed good agreement with SAR images, which allowed building a time series of icebergs distribution fields. In our analysis we highlight the iceberg distribution after the collapse of Larsen-B ice shelf.

ERS-ENVISAT Time Survey of Antarctica and Greenland Ice Sheets with Radar Altimetry.

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Here we present the latest results on the investigation of Antarctic and Greenland Ice sheets change using ERS and ENVISAT altimetry. We build continuous and homogeneous time series of height and other radar altimetric parameters from 1995 to 2010 on every point along the reference repeat track. These volumetric variations compare well to GRACE observed gravity field changes over the overlapping period. The altimeter measurements are validated with the OSCAR validation chain and corrected for echo shape change and geographic non repeat of the tracks following the Along track repeat altimetry procedure. This processing allows a careful handling and provides a large number of observations. Radar properties of the ice sheet surface are found to change very significantly at inter-annual and inter-decadal timescale in some places. We evaluate the impact on the height change estimates and we underline the impressive character of this change which is induced by the snow-atmosphere interactions. This extensive and precise coverage helps us describe at higher resolution the changes in surface height of the ice sheet, delimiting large change areas like quickly changing glaciers and sub-glacial lakes. The larger scale changes are also well described with significant inter-annual and inter-decadal signals observed. The volume change is still not complete since large parts of the coastal areas of the ice caps can't be properly measured with this technique. However when advantages and drawbacks of each altimetry and gravimetry are considered carefully, we find very impressive agreements between both techniques. This allows us to extend some of the interpretations back into the 90s with confidence and better qualify some the observed gravity changes.

Horwath, M., B. Legresy, F. Remy, F. Blarel and J.M. Lemoine. 2012. Consistent patterns of Antarctic ice sheet interannual variations from ENVISAT radar altimetry and GRACE satellite gravimetry. Geophysical Journ. Internaional. In press.

Legresy B., F. Papa, F. Remy, G. Vinay, M. Van den Bosch and O.Z. Zanife. 2005. ENVISAT Radar Altimeter measurements over continental surfaces and ice caps using the Ice2 retracking algorithm. Remote Sensing of the Environment. 95. 150-163.

Legresy B., F. Remy and F. Blarel. 2006.Along track repeat altimetry for ice sheets and continental surface studies. Proceedings of the ESA conf. 15 Years altimetry. Venice.

Validation of ERS and ENVISAT Radar Altimetry for Ice Sheets Applications

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The LEGOS-CTOH maintains and develops the use of satellite radar altimetry over ocean and continental surfaces. Here we show the outputs of a processing chain that has been developed at LEGOS and which we use to qualify the ENVISAT and ERS data over continents and more specifically over ice sheets. The validation is based on a crossover analysis. We briefly describe the steps of the validation process, the results on various parameters, like height, but also backscatter, leading edge and trailing edge of the waveforms and range corrections. The validation process allows us to deliver reports, but also a validation table which is available on our website as well as other meta-products. We show the various aspects of the error budget and decompose it in different sources and for different satellite configurations. In particular, the echo and geographic corrections which we developed are tested on various scenarios. Building these corrections needs a certain number of repeat cycles to be available at each point along the track. We found that a minimum of 25 repeat cycles is necessary to lower down the error budget and statistically separate temporal and geographic variations. Beyond 35 repeat cycles, the error level stabilizes between 10 and 40cm depending on the slope and smoothness of the topography for gentle slopes over most of the ice sheets above 50cm for more heavily rough topography areas and slopes above 12 m/km. We report on the feasibility to integrate these corrections on level 2 products. We propose a scheme to integrate these corrections in future reprocessing of ERS or ENVISAT and for new radar altimetric missions like Sentinel-3 and SARAL-altika.

Horwath, M., B. Legresy, F. Remy, F. Blarel and J.M. Lemoine. 2012. Consistent patterns of Antarctic ice sheet interannual variations from ENVISAT radar altimetry and GRACE satellite gravimetry. Geophysical Journ. Internaional. In press.

Legresy B., F. Papa, F. Remy, G. Vinay, M. Van den Bosch and O.Z. Zanife. 2005. ENVISAT Radar Altimeter measurements over continental surfaces and ice caps using the Ice2 retracking algorithm. Remote Sensing of the Environment. 95. 150-163.

Legresy B., F. Remy and F. Blarel. 2006.Along track repeat altimetry for ice sheets and continental surface studies. Proceedings of the ESA conf. 15 Years altimetry. Venice.

Improvements to Elevation Change Calculations from Radar Altimetry Near the Edges of the Antarctic Ice Sheet.

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Calculating elevation changes, dH/dt, from radar altimetry near ice sheet edges is complicated by variations of the location on the surface to which the altimeter range is measured, compared to the sub-satellite nadir point. Over sloping and undulating surfaces, the measurement comes from the pulse-limited footprint located at the closest point to the altimeter within the beam-limited footprint. The resulting slope-induced elevation error and the horizontal displacement of the measurement from nadir can be calculated from the surface and beam geometry. For calculation of elevation differences, ΔH, at orbital crossovers, the slope-induced elevation errors are the same for each measurement, if the location on the surface is the same on both passes. However, we correct the ΔH for the differential slope-induced error, caused by orbital attitude differences. A second type of variation, caused by leads and lags of the altimeter tracking algorithm, is normally corrected with post-processing retracking algorithms. A third type of variation occurs over surfaces with abrupt elevation changes that are larger than the altimeter range window altimeter and cause the tracker to lock on to the higher (or lower) surface before the abrupt change. For calculation of ΔH, the third type of variation causes unusable ΔH if the measurement for one orbit is within the ice-sheet (or ice-shelf) boundary and the other is outside on sea ice or open ocean. This is most evident at the boundary where one pass is coming from the ocean/sea ice and the other pass is coming from the ice sheet. In this paper, we take into account the horizontal displacement of the measurement from nadir to correctly position the measurement location on the ice sheet and to include additional crossover-point measurements which measure inside the ice-sheet boundary, even though the sub-satellite nadir point is outside the boundary. We first calculate ΔH for 50X50 km cells using all nadir-point crossovers within a capsize defined by a radius of (50-100km) from the center of the cell that are located within the ice sheet boundary. Near the ice sheet edges, this capsize can encompass ice-sheet, sea-ice/ocean , and ice-shelf. The next step selects the additional nadir-point crossovers outside the boundary, for which the pulse-limited footprint, located at the highest elevation within the large (18km+) beam-limited footprint, is inside the boundary on both passes. We identify those additional crossovers by comparing the elevations to an ICESat DEM. We delete ΔH for which one of the elevations is too close to the ocean geoid level and the other is consistent with an elevation on the ice sheet. In some grid cells, this method increases the crossovers used by over 500% having a significant impact on the dH/dt for that grid cell. We show the effect on the calculation of dH/dt for the Pine Island drainage system.

Elevation Change on Greenland's Jakobshavn Glacier derived from ICESat and IceBridge Data

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As a consequence of global warming, major Greenland outlet glaciers are thinning rapidly and speeding up in movement, leading to a terminus retreat and an increased discharge from the interior of the ice sheet. Recent studies indicate that the mass loss of Greenland is likely to make a faster contribution to future sea-level rise than previously believed. Therefore, it is of great importance to monitor the ongoing elevation change of Greenland outlet glaciers to better understand and respond to future climate change. In this study, we present the first estimates of elevation change on the Jakobshavn Glacier from NASA's Operation IceBridge Airborne Topographic Mapper (ATM) system between 2009 and 2010. To assess whether the recent change is in line or deviates from longer-term behavior, we compare the results with those estimated from the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and land Elevation Satellite (ICESat) between 2003 and 2009. In order to mitigate the effects of seasonal differences on the elevation change, ICESat data that were collected during the same season as IceBridge flights were employed. In the estimation procedure, we applied a method which projects near repeat-tracks onto common locations using a Digital Elevation Model to correct for the surface slope. Results from ICESat data show that the speed of thinning in low-elevation areas (<1500m) of the Jakobshavn Glacier has rapidly increased from -0.67 m/yr between 2003 and 2004 to -2.71 m/yr between 2008 and 2009. In comparison, the elevation change in high-elevation areas (>1500m) are more stable and vary only slightly between -0.26 m/yr and 0.21 m/yr. However, the new results from IceBridge and ICESat data demonstrate that the thinning rate of the lower Jakobshavn Glacier seems to have reached an equilibrium at -2.70 m/yr while that of the high-elevation areas reached its maximum at -0.38 m/yr in 2010.

Ultra-wideband Radars for Measurements of Snow Thickness over Sea Ice and Mapping Near-surface Internal Layers in Polar Firn

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We developed two ultra-wideband radars for measurements over sea and glacial ice. One of these radars operates over the frequency range of 2-8 GHz for measuring the thickness of snow over sea ice and mapping near-surface internal layers in polar firn. The other radar operates over the frequency range of 12-18 GHz for high-precision surface elevation measurements over sea and glacial ice. Both systems are designed to operate in FM-CW mode with transmit power of about 200 mW. The unique feature of these systems is an ultra-fast linear chirp of 6 GHz to conduct airborne measurements. We have been operating these systems on long-range aircraft, including the NASA DC-8 and P-3, and a small twin engine aircraft over the last three years and have successfully collected a large volume of data.

Our results show that that we can map snow-air and snow-ice interfaces with the 2-8 GHz system and generate snow thickness estimates for about 60% of flight lines. We also observed that the ultra-wideband Ku-band altimeter can also map snow-air and snow-ice interfaces when the snow is dry and less than about 60 cm thick. Finally, we observed that snow cover has a significant impact on freeboard estimates obtained with Ku-band altimeters.

The results from the ice sheets show that we can map near-surface internal layers to a depth of about 20 m with the 2-8 GHz system and 5 m with the Ku-band system under favorable conditions. In this paper, we will discuss the design that has enabled us to perform airborne measurements with low-power FM-CW radars and present results from sea ice and glacial ice under variety of conditions. We will also show a comparison of Ku-band results with Cryosat data.

Asian Mountain Glacier Elevation Change From ICESat Altimetry and SRTM C/X-band DEMs

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Asian Mountain glaciers cover an area of 50,000 km^2. Over the last 3 decades, increasing temperatures at a rate of 0.3 degrees Celsius per decade have led to significant amounts of glacial melting. The Chinese Glacier Inventory lists 50,000 ice covered polygons, 4000 of those are crossed by ICESat laser altimetry tracks, and 70 glaciers have more than 100 footprints between 2003-2009. We conduct a glacier elevation change analysis from ICESat near-repeat tracks using up to 19 epochs between March 2003 and October 2009. The projection onto a common track is achieved by using either SRTM C-band or X-band DEMs, in particular, the terrain slope derived from the DEM is needed.

Results in regions for which in situ mass balance estimates exist show excellent agreement with the elevation change estimates, e.g. ice elevations of the Lhagu glacier change at a rate of -0.85 m/year compared to field observations for 4 neighboring glaciers at -0.9 m/year water equivalent. For some glaciers, the near repeat-track analysis fails for several reasons, i) the glacier's DEM/slope is inaccurate, ii) the glacier has changed slope naturally since the DEM data was acquired, iii) the satellite tracks cross the glacier in areas of high terrain variability. We present slope error estimates introduced by both SRTM C-band and X-band DEMs based on a validation study in terrain where more accurate slope information is available. For selected glaciers, we identified significant elevation loss even under the consideration of slope errors. Satellite Laser altimetry is able to provide elevation change data of mountain glaciers in addition to the already observed increase in lake levels.

Poster Session: The Future of Altimetry

Finer, Better, Closer: Advanced Capabilities of SAR Altimetry in the Open Ocean and the Coastal Zone

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SAR altimetry promises to deliver FINER along-track spatial resolution, BETTER range retrieval performance and valid data CLOSER to the coast than is possible with the conventional pulse-limited altimeters that have flown for more than 20 years. The Cryosat-2 SIRAL altimeter represents the first opportunity to test these notions with observations, thanks to altimeter data collected in SAR mode over a number of ocean and coastal regions. The Cryosat-2 SAR mode is a precursor for the SRAL altimeter on the GMES Sentinel-3 Surface Topography Mission (STM) and of the SAR altimeter on the Jason-3 follow-on mission, Jason-CS. The improved capabilities of SAR altimetry open appealing prospects in particular for coastal oceanography and ocean bottom topography applications.

Cryosat-2 has been providing SAR altimeter waveforms to the science community continuously since July 2010. This paper presents analyses of the retrieval performance for sea surface height (SSH) and significant wave height (SWH) of Cryosat-2 SAR mode compared to Jason-2 over the open ocean and in various coastal regions. The paper discusses how Cryosat-2 L1B SAR waveforms are retracked using theoretical models to retrieve ocean geophysical parameters from peaky SAR waveforms. We consider the sensitivity of SAR mode altimetry to antenna mispointing and to ocean wave conditions and quantify the retrieval errors and biases in Cryosat-2 SAR mode data using independent validation datasets from in situ and other independent sources. This comprehensive assessment of Cryosat-2 SAR altimetry in the open ocean and the coastal zone helps to highlight opportunities and challenges introduced by this step change in altimeter technology when it comes to building long-term altimetric records.

Maximizing the Intrinsic Precision of Radar Altimetric Measurements

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The intrinsic precision of a radar altimeter's measurement (such as sea surface height or significant wave height) is determined by the number of statistically independent looks at each resolved surface location. A radar's precision improves in direct proportion to the square root of the number of such looks contributing to the measurement average. Maximizing precision implies maximizing the number of looks. For conventional (incoherent) altimeters such as TOPEX, the number of independent waveforms per unit of time is limited by the Walsh upper bound on the radar's pulse repetition frequency (PRF). For advanced (delay-Doppler, or SAR-mode) altimeters, the transmitted pulses are grouped into bursts, whose received signals are subjected to coherent processing techniques that sort the data into discrete along-track Doppler bins. In this context within each burst the PRF may exceed the Walsh upper bound since the waveforms in the Doppler bins are statistically independent. The number of looks in this scenario is proportional to the burst rate, thus inversely proportional to burst period. One may derive a generalized Walsh lower bound on burst period which assures that the post-processing waveforms from all resolved Doppler bins are statistically independent. The maximum number of looks is achieved when the burst period is at the generalized Walsh limit. The closed-burst strategy (such as is used on CryoSat for example) constrains the burst period to be approximately three times larger than the generalized Walsh lower bound. Open-burst operation would allow the capture of nearly all available looks, an improvement in this case by a factor of three, thus maximizing the precision of the radar's measurements. Given an open-burst approach, conservative radar design leads to an altimeter whose pulse-repetition frequency should be less than the usual Nyquist lower bound. This condition would not be admissible for an imaging system whose targets fill the radar's unambiguous range/Doppler space. However, for an altimeter viewing surfaces that have relatively small topographic relief such as typical oceanic surfaces, the Nyquist PRF lower bound may be relaxed with no negative consequences. Potential azimuth (Doppler) ambiguities may be rejected by range gating. Synchronization of the receive windows so that they fall between transmissions may be achieved by small burst-to-burst adjustments of the burst period to compensate for variations in the radar's altitude over the mean sea surface. Thus, an altimeter's maximal precision is achieved by a coherent radar architecture, operating in open burst mode, whose PRFs within each burst are less than the conventional Nyquist lower bound.

Sentinel-3 Surface Topography Mission: Payload, Data Products and Cal/Val preparation

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Sentinel-3 is an Earth observation satellite mission designed for GMES to ensure the long-term collection of high-quality measurements delivered in an operational manner to GMES ocean, land, atmospheric, emergency and security services. Primary sentinel-3 topography mission measurement requirements have been derived from GMES user needs as follows:

- ☐ Sea surface topography (SSH), significant wave height (Hs) and surface wind speed derived over the global ocean to an equivalent accuracy and precision as that presently achieved by ENVISAT Radar Altimeter-2 (RA-2).
- ☐ Enhanced surface topography measurements in the coastal zone, sea ice regions and over inland rivers, their tributaries and lakes. To address the above requirements, the Sentinel-3 Topography payload will carry a Synthetic Aperture Radar Altimeter (SRAL) instrument, a passive microwave radiometer (MWR) a GPS receiver and laser retro-reflector for precise orbit determination providing continuing the legacy of ENVISAT RA-2 and Cryosat.
- ☐ Three level of timeliness are defined within GMES for the S-3 Topography mission:
- ☐ NRT products, delivered to the users in less than 3 hours after acquisition of data by the sensor,

- Short time critical (STC) products, delivered to the users in less than 48 hours after the acquisition and,
- Non-time critical (NTC) products delivered not later than 1 month after acquisition or from long-term archives.
- The Sentinel-3 topography data products will provide continuity of ENVISAT type measurement capability in Europe to determine sea, ice and land surface topography measurements with high accuracy, timely delivery and in a sustained operational manner for GMES users. The Sentinel-3 data will also provide fundamental inputs to a variety of value-adding downstream services for industry, government agencies, commercial users, service providers and appropriate regulatory authorities.

The Calibration and Validation of the Sentinel-3 topography products will nominally rely on the cross-comparison with the ESA Envisat Altimetry mission and will be a significant challenge due to the stringent S-3 mission measurement requirements and their safeguarding all over the mission lifetime.

Calibrating and Validating SWOT, the Next-Generation Altimetry Mission

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The notable accomplishments of satellite altimetry, such as the identification of multi-decadal sea-level rise trends, have been enabled, in part, by a vigorous calibration and validation effort from joint efforts from international project teams and the science community. The Surface Water and Ocean Topography (SWOT) mission represents the next step in altimetry, extending the profiles collected by traditional altimeters to swath coverage, allowing the global study of small mesoscale and submesoscale phenomena. In addition, SWOT will extend the capabilities of traditional altimetry to enable the global mapping of water bodies with area greater than $(250m)^2$ and rivers whose width is greater than 100 m.

The science goals for SWOT require global consistent calibration over a large swath, as well as the characterization of the systematic spatial variability of the errors at scales on the order of a few kilometers. Traditional altimetry calibration and validation have concentrated on either point sites (e.g., the Harvest Platform) or consistency with measurements at basin or global scales. It is clear that these approaches need to be complemented to calibrate and validate SWOT.

To achieve this extension, we propose a solution that relies on two key components. The first is the use of global cross-over analysis with the conventional satellite constellation and the conventional altimeter onboard SWOT. This calibration will allow the calibration of the SWOT mean sea level, monitor instrument drift, and provide validation of the stability of cross-track systematic errors due to instrument roll biases and the interferometric phase screen. To provide calibration and validation of the errors at small scales (100 km to 1 km) a new approach is required. We are in the process of developing an airborne platform, AirSWOT, which will provide SWOT-like measurements with precisions that exceed that expected from SWOT, but with potential drifts at longer wavelengths. These longer wavelength drifts and biases will be corrected using the conventional altimeter constellation (for ocean sites) or in situ data provided by high accuracy digital elevation models (for land sites).

In this presentation, we will review the SWOT calibration and validation plan, providing the methodology for the validation of the various components of the SWOT error budget over land and ocean. We will describe the measurement capabilities, errors, and validation plans for the AirSWOT platform. We hope to also provide the first example data collected by AirSWOT during its summertime engineering checkout flights.

Reaching Sub-Centimetre Range Noise on Jason-CS with the Poseidon-4 Continuous SAR Interleaved Mode

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The benefit of the SAR mode for ocean altimetry was identified back in 1998 in an empirical manner [1]. In 2007, the mathematical framework including accurate numerical re-tracking of SAR echoes was given in [2]. The predicted accuracy for range was below the centimetre for a SIRAL/Cryosat configuration. With the launch of Cryosat-2 and thanks to the availability of SIRAL-2 altimeter raw data, it was demonstrated in [3] that the range and significant wave heights noises were in very good agreement with the theoretical expectations of [2]. Similar results were also presented by scientific groups at the OSTST 2011. This rapid breakthrough has triggered a profound interest among worldwide scientists as the range noise improvement compared to conventional altimeters can be reduced by a factor 2 for SIRAL and a factor of 3 for future missions as Jason CS .

Jason CS, CS standing for continuity services, is the successor of the Jason 1-3 reference missions. The primary objective of Jason CS is to ensure, as a minimum, the same level of data quality. This operational need has been taken as the driver for the design of Poseidon-4, the altimeter of Jason CS. In particular, the along track sampling of the ocean shall be maintained identical to previous Jason series, i.e. around 2 kHz in Ku band and around one every 7 pulses in C band. A SAR mode is also requested for Jason CS, but primarily this mode was thought to be activated only in coastal areas. With the clear in flight demonstration of the SAR mode capability over open ocean brought by SIRAL-2, it became clear during the early study phases of Poseidon 4, that a continuous SAR mode operation was desirable while care shall be taken not to perturb the operational mission objectives. To respond to that constraint, TAS proposed to ESA to introduce a SAR mode operating in the so-called "interleaved mode" where, at the difference of SIRAL, echoes from the ocean are received in between each transmitted pulses. In addition it is also demonstrated that the Pulse Repetition Frequency can be much lower (about a factor 2) than the Nyquist Doppler bandwidth.

This paper will present the rationale for the functioning point of the altimeter and the expected performances in terms of range and SWH accuracies. The results are supported by accurate simulations, and by correlations with the results obtained on in flight SIRAL-2 data. Moreover, sensitivity to antenna pointing and the capability to extract the pointing from the data will also be presented and discussed.

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[2] Phalippou and Enjolras, Re-tracking of SAR altimeter ocean power-waveforms and related accuracies of the retrieved sea surface height, significant wave height and wind speed. IGARSS 2007.

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Swim, the First Ever Spaceborne Waves Scatterometer Radar, now under Development

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The instrument SWIM (Surface Waves Investigation and Monitoring) on the CFOSAT program (China France Oceanographic Satellite) is a state of the art radar. At first, SWIM is the first ever space radar concept that is mainly dedicated to the measurement of ocean waves directional spectra and surface wind velocities through multi-azimuth and multi-incidence observations. Orbiting on a 500 km sun-synchronous orbit, its multiple Ku-band (13,575 GHz) beams illuminating from nadir to 10º incidence and scanning the whole azimuth angles (0-360º) provide with a 180 km wide swath and a quasi global coverage of the planet between the latitude of –80 and 80º.

Secondly, such a wide range of observations requiring high range resolution (about 20 m on the ground) have led to design an instrument whose architecture and technology go beyond what have been done on altimeter and scatterometer systems.

The global coverage and the reduction of telemetry budgets have required performing onboard range compression. The variety of signals at different incidences, the impact of the complex moving geometry of observation and the required real-time signal processing have led to propose onboard complete digital range compression on backscattered 320 MHz bandwidth signals. The design of the onboard compression and processing resulted from a trade-off between the instrument high level performances required, the needed correction for geometrical effects such as range migrations and performance of the acquisition and tracking loops.

Finally, multi-azimuth multi-incidence observations requirements have led to design an ambitious antenna subsystem that rotates at 5,6 rounds per minute while transmitting high power RF signals towards tunable directions.

Thales Alenia Space started in January 2009 under CNES contract phase B studies on the design of the instrument that have led to a System Preliminary Design Review in January 2010. We have now started the development phase of the instrument (the C/D phase) since January 2011.

This paper will aim at giving an overview of the current phase CD development that are performed at Thales Alenia Space. It will emphasize the state-of-the-art architecture of the SWIM instrument, the last outcomes of design and the last updates of performances estimation.

A first section will recall SWIM main parameters and operating modes. A second section will then provide with the most update architecture, especially stressing the state-of-the-art improvements proposed on the Radio Frequency Unit (RFU), the Digital Processing Unit and the complex rotating antenna subsystem. A third section will deal with the Digital Processing Unit (DPU), characterized by a complex onboard processing. A last section will show outputs of instrument performances, showing on the one hand the validation of the onboard processing, and on the other hand samples of radar echoes from which the scientific products are retrieved.

SENTINEL-3 Topography Mission Payload, Where we are.

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Initiated in 2006 for phase B, the Sentinel-3 satellite has now passed the CDR phase and the payloads have now reached the Flight Models testing phase. In parallel of payload procurement, Thales Alenia Space is coordinating the development performed by CLS of the associated Ground Processor Prototypes up to L1 and System Performance Simulator which have been recently released to Agency to prepare the operational processing.

The paper will present the current definition and status of the topography package payload of Sentinel-3 comprising the Sar Radar Altimeter (SRAL) provided by Thales Alenia Space, the MicroWave Radiometer (MWR) provided by Eads Casa Espacio, GPS receiver provided by Ruag Space and Laser Retro-Reflector. For Sentinel- 3 A and B models, the payload will also comprise a DORIS instrument provided by CNES as CFI.

An overview of the Level 0 and Level 1 prototyping activities status and on-going and future activities for ground segment support will also be presented, along with the System Performance Simulator tool which is able to generate science realistic telemetries of the instruments to be ingested in the L1/L2 prototypes.

KARIN: The Ka-band Radar Interferometer for the Proposed Surface Water and Ocean Topography (SWOT) Mission

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Over the last two decades, several nadir profiling radar altimeters have provided our first global look at the ocean basin-scale circulation and the ocean mesoscale at wavelengths longer than 100 km. Due to sampling limitations, nadir altimetry is unable to resolve the small wavelength ocean mesoscale and sub-mesoscale that are responsible for the vertical mixing of ocean heat and gases and the dissipation of kinetic energy from large to small scales. The proposed Surface Water and Ocean Topography (SWOT) mission would be a partnership between NASA, CNES (Centre National d'Etudes Spaciales) and the Canadian Space Agency, and would have as one of its main goals the measurement of ocean topography with kilometer-scale spatial resolution and centimeter scale accuracy. In this paper, we provide an overview of all error sources that would contribute to the SWOT mission for the ocean.

The core technology for the proposed SWOT mission would be the Ka-Band Radar Interferometer (KaRIn) instrument, originally developed from the efforts of the Wide Swath Ocean Altimeter (WSOA). While conventional altimetry relies on the power and the specific shape of the leading edge of the return waveform, which is only available for the nadir point, the interferometric technique relies on the measurement of the relative delay between the signals measured by two antennas separated by a known distance (hereafter termed "baseline"), together with the system ranging information, to derive the height for every imaged pixel in the scene. For a given point on the ground, a triangle is thus formed by the baseline B, and the range distance to the two antennas, which can be used to geolocate in the plane of the observation. Using two consecutive radar pulses, one from each antenna, to form the interferometric pair (this operation mode is commonly referred to as "ping-pong mode"), the range difference between the two antennas is determined by the relative phase difference between the two signals. The total swath coverage provided by the interferometer would be 100 km (50 km on each side of the nadir track, with a gap of 20 km in the center which is covered by the nadir altimeter), at an unprecedented resolution of 1 km for the ocean (after on-board processing), and 100 m for land water, both with centimetric accuracy. In this paper, we present an overview of the KaRIn instrument, key performance requirements and the associated error budget.

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SRAL Latest Results on EM and PFM Models

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Developed in the frame of the Global Monitoring for Environment & Security (GMES) initiative, SRAL, the radar altimeter instrument of the Sentinel-3 topography mission, aims to provide not only Sea Surface Height (SSH) and Sea Wave Height (SWH) measurements over ocean and coastal zones but also range measurements over sea ice, ice sheets and in-land waters.

The SRAL measurement modes include two radar modes consisting of :

- ☐ the conventional Low Resolution Mode (LRM) as for the ENVISAT/RA-2 and JASON/Poseidon instruments,
- ☐ the SAR mode allowing enhanced resolution along-track as for the CRYOSAT/SIRAL altimeter currently in operation.

Each radar mode is operated either in a closed-loop tracking fashion (autonomous tracking of the ground echo) or in an open-loop fashion by using a priori knowledge of the satellite height and of the terrain elevations. Direct transitions are implemented in order to minimise the transition times between two modes. The SRAL mode diagram including the measurement and the calibration modes will be presented.

The validation of the SRAL Engineering Model (EM) was successfully completed a few months ago. The performance results obtained on this model, such as Range & Azimuth Impulse Responses, the receive transfer function and the range accuracy, will be reviewed. The validation of the tracking performances in Closed-Loop and Open-Loop with the associated scenarios will also be explained in the current paper.

In addition, the SRAL Proto-Flight Model (PFM) tests sequences are now about to start and the results which will available within a few months will be presented.

Tropical Atlantic Regional Studies using SARAL/Altika

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Previous studies have evidenced the complexity of the tropical Atlantic Ocean variability, both in time and in space. Thanks to altimetry missions such as TOPEX/Poséïdon, Jason1&2, ERS1&2, ENVISAT, associated with in situ experiments (ARAMIS, EGEE-AMMA, PIRATA...) and numérical model results (Clipper, Drakkar, Mercator Océan...), important progresses have been accomplished these last years to demonstrate the ability of using altimetry in the tropics, and to document large scale oceanic processes. Knowledge of equatorial mass and heat transports, tropical wave phenomena for instance has been improved thanks to these combined efforts.

The new coming SARAL Altika altimetric mission aims to provide data complementary to Jason 2 as a follow-on to the successful couples previously evocated. But its characteristics will offer higher performances useful in coastal oceanography. This proposal intends to analyze the impact of this new generation altimeter in 4 regions of the tropical Atlantic ocean. Region 1 is located on the western side of the basin, in the North Equatorial CounterCurrent retroflexion area. This region is known for its intense meso-scale variability. Regions 2 and 3 are characterized by local upwellings (Mauritania and Benguela). Region 4, along the northern coast of the Gulf of Guinea, presents a large range of ocean dynamics. These regions benefit from quite a number of in situ data thanks to oceanographic cruises, moorings and floats. High resolution numerical models have also been run and/or regional models been locally adapted. Thus a combined approach using in-situ data, multi-satellite data, numerical model results, mathematical approach such as neuronal inversion together with the SARAL Altika altimetry will be apropriate both to validate the altimeter in producing oceanic meso-scale information in a tropical and rainy environment, and then to obtain more information on these dynamics and variabilities.

CRYPTIC - Ingestion System for Cryosat2 SAR Full Bit Rate data

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The launch of CryoSat-2 has provided a dataset with a unique insight into the changes taking place over not just the cryosphere, but also the oceans, land and inland water. However, ingestion of the data into processing schemes is a complex task with multiple official libraries required simply to access the data. From a systems perspective, the critical dependency on IDL code results in an inefficient and cumbersome multi-stage preprocessing schema.

In an effort to simplify this process a new library has been created using the C programming language - CRYostat-2 Processing and Transfer Ingestion Code (CRYPTIC); capable of ingesting both SAR Full Bit Rate and SAR Level 1B data, using a minimal number of files. It is proposed to provide this code, when fully validated and tested, to the scientific community to assist in unlocking the potential of the information provided by the CryoSat-2 satellite, particularly in the unique SAR FBR datasets.

This paper presents an overview of the processing chain developed for this library and showcases initial results from CryoSat-2 SAR FBR waveform reconstruction and analysis. Within the EAPRS Lab, data are then piped into the Berry Expert System (BES), processed and retracked. This paper also presents results from an initial BES analysis of SAR FBR data over the Mekong Delta. Sample results are presented for both coastal and land SAR FBR waveforms.

Exploring the Benefits of Using Cryosat's Cross-track Interferometry to improve the Resolution of Multi-satellite Mesoscale Fields

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Sea surface height (SSH) measurements provided by pulse-limited radar altimeters are one dimension profiles along the satellite's nadir track, with no information whatsoever in the cross-track direction. The anisotropy of resulting SSH profiles is the most limiting factor of mesoscale SSH maps merging 1D profiles.

In this paper we explore the potential of the cross-track slope derived from Cryosat's synthetic aperture radar interferometry (SARin) mode to increase the resolution of mesoscale fields in the across-track direction.

Through idealized 1D simulations, we show that it is possible to constrain mesoscale mapping in the across-track direction with the new SARin parameter. An error-free slope allows a single SARin instrument to recover almost as much SSH variance as two coordinated LRM sensors. Noise-corrupted slopes can also be exploited with a mapping performance breakthrough in the 1 to 5 µrad range (for 150 km radius features in strong currents), which might be at the limit of the capabilities of current Cryosat datasets (after cross-calibration and along-track filtering).

The main benefit of using Cryosat's SARin slope would be to reduce the influence of the mesoscale observation gaps created by the satellite track aggregation in any 10 to 20 day window. However SIRAL's SARin slopes would be more desirable on a TOPEX/Jason orbit (e.g. for Jason-CS) than on Cryosat's orbit because the former has a 300 km cross-track resolution where the SARin slope is more beneficial.

Altimeter Constellations: Sampling Capabilities and Complementarity with SWOT

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Conventional altimetry constellations with 2 to 4 sensors have been providing medium resolution information for 15 years. However new areas of studies are emerging and are highlighting the need for higher resolution datasets, both in space and in time.

An ambitious way to improve the spatial resolution is SWOT's wide-swath technology which provides an extremely high resolution topography image every 22 days. However small spatial scales are often associated with high frequency that a single sensor cannot resolve globally. The same stands for hydrology where revisit time can be an asset for even detection and monitoring.

Large constellations of small satellites can resolve short time scales more easily. They also offer a more flexible space vs time sampling trade-off, and the ability to coordinate multiple sub-constellations with different objectives. The short revisit time associated to large constellation is to be balanced by a much lower spatial resolution than wide-swath altimetry, and small satellite may not benefit from state-of-the-art doppler altimetry. To that extent, both systems are complementary approaches to monitor new fractions of the variability spectrum. Furthermore, assuming that a wide swath sensor and a constellation of small satellite could fly together, the constellation of traditional pulse-limited altimeters could significantly simplify the error reduction of a wide-swath sensor in the 100 to 300 km wavelength band, thus giving wide-swath altimetry a stronger focus on small scales, for a higher overall accuracy and simpler system design.

The purpose of this paper is to look beyond conventional altimetry, and to define constellation baseline(s) able to provide high spatial and temporal sampling, and more importantly to meet altimetry user requirements both operational and for new areas of research. This work also highlights many practical benefits such as the resilience of the observing system, a very attractive cost / service ratio for a sustainable Near Real Time observing system able to complement technology demonstrators and innovating missions.

Monitoring of Wave Fields with Swim on CFOSAT

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The Chinese and French Space Agencies propose to jointly carry out an innovative mission, CFOSAT (China France Oceanography Satellite project) devoted to the monitoring of the ocean surface and its related science and applications. Feasibility and Preliminary Design phases were successfully achieved from 2006 until 2009. The project started Detailed Design phase C beginning of 2011 which will be immediately followed by the Manufacturing Phase D. The launch and the Assessment Phase completion should lead to deliver a fully validated system on orbit in 2015.

The primary objective of CFOSAT is to monitor, at the global scale, ocean surface winds and waves so as to improve: wind and wave forecast for marine meteorology (including severe events), ocean dynamics modeling and prediction, climate variability knowledge, fundamental knowledge of surface processes, etc. As an opportunity, CFOSAT will also be used to complement other satellite missions for the estimation of land surface parameters (in particular soil moisture and soil roughness), and polar ice sheet characteristics.

The satellite embarks two payloads; both are Ku-band (13.2 to 13.6 GHz) radar scanning around the vertical axis:

- the wave scatterometer SWIM, a rotating 6-beams radar at small incidence (0 to 10°) [1,2],
- the wind scatterometer SCAT, a fan-beam radar at larger incidence angles (45 and 49°) [3].

In this paper, after a presentation of the CFOSAT mission and the associated scientific requirements, a focus on the SWIM (Surface Wave Investigation and Monitoring) instrument, developed by Thalès Alenia Space under CNES contract, and its performances will be done.

SWIM enables the measurements of significant wave height and wind speed, both with the nadir beam signals, directional wave spectra with the 6°, 8° and 10° beams signals and backscattering profiles from 0° to 11° with the six beams signals. The main principles of the measurement will be explained and illustrations on simulated data will be discussed. Eventually, the paper will conclude on a discussion on the instrument and science performance that can be reached with SWIM.

CFOSAT is an innovative mission jointly developed by CNES & CNSA. The unique combination of instruments will allow to determine the directional wave spectra of waves in relation with surface winds. The application field sounds promising both for operational and research purposes.

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Altimeter Mission end-to-end Simulators: interesting Tools to assess global Performance and develop new Algorithms for future Missions

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In the last two decades, several simulation activities have been conducted by CLS (under either CNES, ESA or TAS funding) with the objectives to assess end-to-end mission performances, to develop and analyze new processing algorithms and also to evaluate the impact of physical phenomena or instrumental effects on the performance.

The methodology has been successfully used for conventional altimeters (Jason 1/2 and Envisat/RA-2 instruments), Doppler altimeters (CryoSAT and Sentinel-3), Wide Swath interferometric altimeters (WSOA and SWOT configurations) and radiometers (SARAL/AltiKa, Sentinel-3). CLS has also participated in the development of the SWIM simulator (on board CFOSAT mission).

The end-to end simulators have three main components:

- ☐ a scene generator module including surface (ocean, sea-ice, ice sheet, land, lakes,) geometrical and electromagnetic characteristics, and propagation perturbations (troposphere through a radiative transfer model, ionosphere, rain cells ...);
- ☐ an instrument module including the antenna characteristics and the instrument onboard processing (range and gain tracking, range impulse response, quantification, thermal effects ...);
- ☐ a processing module up to the geophysical parameters (signal processing and geophysical parameters estimations).
- ☐ For example, those simulators have already been used to analyze the sea state bias on the altimeter geophysical estimates in the case of conventional altimetry and future AltiKa and SWOT missionss. In the field of Doppler altimetry, they are helping us to test and develop the SAR processing algorithms and are being used for the development of new retracking techniques over ocean. Those simulators have also been extended to coastal, inland water and ice areas and are used for the analysis of the estimation algorithms.

Finally, regarding the instrument processing, those simulators are very useful for the analysis of the onboard tracking algorithms and for the development of corrective algorithms of the onboard effects.
This paper will provide an overview of such end-to-end simulators and their main application studies and the corresponding achievements.
Examples will be provided showing the importance of mastering the simulated effects depending on the analysis objectives.
Finally, we will give some perspectives studies using end-to-end simulators for the development of the future missions.

Sentinel-3 Surface Topography Mission System Performance Simulateur and Ground Prototype Processor and Topography Expertise

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Sentinel-3 is an operational GMES satellite program for continuity of the successful series of ERS and Envisat Altimetry. In order to assess and control the expected Altimeter System performance, a dedicated System Performance Simulator (SPS), including Ground Processors Prototype (GPP), is designed for each instrument of the topography payload (SRAL, MWR and GNSS). This activity is performed by CLS (with a support of a European consortium) under a Thales Alenia Space contract for ESA (end customer) and an ESRIN/CNES contract.

The GPP processes data provided as Instrument Source Packet stream (ISP) to generate level 1b and level 2 products to estimate the measurement errors.

The SPS includes the GPP as well as a scene generator and an instrument simulator to create the necessary ISP streams, representative of geophysical mission data products, to obtain early end-to-end measurements errors estimate before in orbit commissioning. The SPS and GPP are capable of generating Instrument data and the corresponding L0, L1b and L2 products for all the modes and at any location of Sentinel 3 orbit including coastal, inland water, sea ice and ice-sheets.

The three simulators can work autonomously but a coupling is possible between the three instruments which allow the analysis of the behavior of the three instruments in the same geophysical conditions. In the frame of this activity, a Calibration Validation plan has been proposed and a first analysis of the end-to-end performance budget is being performed.

The SPS and the GPP processors have been successfully validated and delivered to TAS/ESA in 2011.

The next step is to check the instruments performances with respect to mission requirements and also to support the ground processing development.

This paper will describe the major elements and functions of these simulators by focusing on the new implemented algorithms and the new product. We will also present the main results regarding the performance assessment.

Altimeter Calibration and Tectonics Inference Oceanographic Network (ACTION) for SWOT

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The eastern Mediterranean Altimeter Calibration network-eMACnet, was the result of international collaborative efforts in the Aegean since 2001. Initially we established a permanent absolute calibration facility south of Crete, Greece on the isle of Gavdos, followed by a second site at Kasteli, in collaboration with the Tech. Univ. of Crete, and equipped with GNSS Continuously Operating Reference Stations (CORS). Since 2008 the Nat. Tech. Univ. of Athens (NTUA) joined us expanding the network with an immediate addition of four tide gauge sites which we proceeded to equip with CORS GPS: at PALEKASTRO, MANI-KARAVOSTASI, EMPORIO-CHIOS, and THASOS. Additional tide gauges and GNSS will be deployed at KYMI-EVIA and NEA SKIONI, before the end of 2012. The primary purpose of the extended network is the absolute calibration and validation of altimetry missions through the continuous monitoring of sea level and tectonics at locations near the OSTM mean groundtrack. The CORS positioning ties our network to the ITRF, so that our sea level observations contribute in addition to absolute calibration of altimeters, to global change observations that are of importance to global international initiatives, as well as absolute sea level studies of the region. This Aegean-wide network samples at the moment the OSTM/Jason-2 tracks 18, 33, 94, 109, and 185, some of them in more than one location. It will support current and future altimeter missions JASON-2/3, ENVISAT, Cryosat-2, HY-2A, JASON-CS and SWOT, especially the latter, requiring calibration over an area rather than a single track. By 2020, the ACTION network will provide a well-understood environment for a successful Cal/Val phase of a complex mission such as SWOT. We will expand our consortium with additional local groups and agencies operating sea level monitoring networks in the area: the Hellenic Navy Hydrographic Service (HNHS) and the Hellenic Center for Marine Research (HCMR). In discussions with HCMR we have reached agreement for the future use of their open-sea buoys once we outfit them with CORS GNSS receivers. HNHS, jointly with NTUA submitted a proposal to obtain new, state-of-the-art tide gauges with GNSS receivers to replace old equipment throughout the Aegean and NTUA in a second proposal, seeks funds for additional buoys and equipment for open-sea environmental monitoring in collaboration with HCMR. NTUA will also provide absolute gravimeters to complement the geometric measurement of height changes, and Ocean Bottom Pressure gauges installed at the HCMR buoys for amongst other uses, support for mass redistribution studies (in connection with GRACE and GRACE FO). ACTION builds upon the existing equipment, facilities and access-to-data of the previously NASA/EU-funded GAVDOS, DynMSLAC, and eMACnet projects, and relies heavily on collaborations with other European and OSTM Cal/Val groups. Our facilities contribute the collected data to many other projects (CLIVAR, IOC, GCOS, GOOS, GGOS, etc.).

The Surface Water / Ocean Topography Mission (1): Science Processing and Data Products

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The Surface Water / Ocean Topography (SWOT) mission, a proposed partnership between NASA, CNES (Centre National d'Etudes Spaciales), and the Canadian Space Agency, promises to provide first-of-their kind measurements of rivers to 100 m, lakes to 250 m, and sea surface topography to 1 km or better scales globally and repeatedly. The fine scale of the measurements would result in large data volumes starting at the spacecraft and flowing through all links of the ground system. Furthermore, the centimetric height accuracy required means that all features of the processing must be considered carefully.

We will provide an overview of the data flow from the proposed spacecraft to the science processing center. We will describe the architecture of the processing system and the main processing steps for both the ocean and land data. All data would be processed on a swath basis as soon as precision orbit information and ancillary data are available (approximately 10 days in order to have crossover calibration data). Finally, we will give an overview of the data products. The Geophysical Data Record (GDR, Level 2) for the ocean is a relatively straightforward extension to the swath geometry of the traditional ocean altimeter (TOPEX, Jason) GDR. However, the hydrology data product poses unique challenges with its requirement for 50 m posting of water heights. It is not feasible to make this product as a raster, so it would be made as a triangularly interpolated network (TIN) with location, elevation, classification, associated metadata and errors in the estimates for areas within and near water detected in the SWOT swath. Approaches to providing additional easier-to-use information for hydrologists such as:

(1) shapefile polygons for all lakes/reservoirs/wetlands;

(2) shapefiles for rivers with associated reach averaged discharge information based on Manning's equation;

(3) floodplain geometry from the TIN will be described.

All data products would be produced for each 22-day cycle enabling the calculation of surface water storage change on monthly time scales. Methods for updating the discharge product as improved coefficients become available will also be discussed.

Some of the work reported here was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. (1)The SWOT mission has not been formally approved by NASA. The decision to proceed with the mission will not occur until the completion of the National Environmental Policy Act (NEPA) process. Material in this paper related to SWOT is for information purposes only.

The SWOT Mission Concept Description

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The Surface Water and Ocean Topography (SWOT) is a planned satellite mission to study the world's oceans and terrestrial surface water bodies. It is being developed as a cooperative effort between NASA and CNES. The primary objectives of the SWOT mission are to characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and larger, and provide water surface elevation, as well as fresh-water discharge and storage change in lakes, reservoirs, wetlands, and rivers at the global scale. SWOT observations will be acquired for a period of at least three years after launch, which is scheduled end of 2019.

The purpose of this paper is to present the current SWOT mission concept per Mission Concept Review status, including technical development challenges regarding the Pay-load Instrument, Spacecraft and the ground data system.

Poseïdon4 on Jason-CS Altimetry Mission - Altimeter Architecture, Operational Modes & Anticipated Performances

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Jason-CS (Continuity of Service) will provide data and services to ensure continuity of the operational oceanography enabled by the Jason-1, -2 and -3 satellites (Jason-3 still being in development). It's main payload instrument is the Poseidon-4 altimeter (POS4).

The design proposed for the POS4 altimeter represents a further development step in the Poseidon product line of altimeters, now merged with the SAR altimeters of CryoSat and Sentinel-3. These developments are both technological and functional: they provide enhanced performance and capabilities.

In terms of technology, the division between digital techniques and high-frequency analog electronics has been reassessed. The new "Digital" architecture takes over some previously-analog functions (with their associated tuning effort) and allows the "deramp" approach, introduced in SeaSat to overcome technology limitations, to revert to the more classical matched filter approach. As well as implementation advantages this has a direct effect on performance, offering increased stability and signal quality.

Some of this technology will be embarked in a French national scatterometer project, SWIM, and other elements are new developments for POS4.

A further development, still in the study phase, is the so-called Interleaved Mode. Here the pulse timing (the "chronogram") is adapted to implement SAR mode and the familiar pulse-width limited (now called Low Resolution Mode) at the same time. This offers a dramatic improvement in system capability. Full continuity with the previous Jason missions is guaranteed with the LRM, while the advantages of SAR mode in spatial resolution and particularly in the reduced height noise (by a factor of 2 or 3) will be provided in a parallel data stream.

The Interleaved Mode does have some impact on system resources and on-ground data processing, and these are also being assessed.

This paper will present all of these aspects of the new Poseidon-4 altimeter.

Doppler Altimeter Data over Ocean, Processing Strategy and Associated Performance

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The Delay Doppler/SAR radar altimeter concept has been first proposed by Raney (1998) demonstrating theoretically higher precision and resolution capabilities than what is typically seen with conventional pulse limited altimeters. This novel concept is now, and for the first time, implemented in a spaceborne altimeter, named SIRAL, operating on board Cryosat-2 mission for sea ice thickness monitoring purposes. On-board the future Sentinel-3 mission (to be launched in 2014), this mode will be implemented and will be devoted to sea ice but also to coastal and inland water areas. Although the technique of using SAR radar altimeter has been subject to significant research demonstrating high improvements for the sea ice observations, very few studies have been devoted to the analysis of this technique and its performances over the ocean surface which is of high importance for Sentinel-3 mission. Recently, several studies have been initiated and are ongoing to develop and test the most suitable processing algorithms for this new altimeter mode, with the final objective to achieve the theoretical performance of the SAR radar altimeter over ocean. CLS has been conducting a study under CNES funding for the development of a new retracking technique of the SAR mode data over ocean. This study has been using simulated SAR mode waveforms and Cryosat-2 flight data provided by the CryoSat project. This paper will present the new developed technique - in particular the retracking approach - and the corresponding performance over ocean.

Automatic Calibration of Global Flow Routing Model Parameters in the Amazon Basin using Virtual SWOT Data.

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The Surface Water and Ocean Topography (SWOT) mission is a swath mapping radar interferometer that will provide global measurements of water surface elevation (WSE). The revisit time depends upon latitude and varies from two (low latitudes) to ten (high latitudes) per 22-day orbit repeat period. The high resolution and the global coverage of the SWOT data open the way for new hydrology studies. At this stage of the mission, it is crucial to quantify the impact of the SWOT data for the modelling of the hydrodynamics of an hydrological catchment. Here, the aim is to investigate the use of virtually generated SWOT data to improve the simulation of water heights and discharge by the automatic calibration of model parameters on the Amazon catchment area. The Hydrological Modeling and Analysis Platform (HyMAP) has a 0.25-degree spatial resolution and runs at the daily time step to simulate discharge, water levels and floodplains. The surface runoff and baseflow drainage, derived from the Interactions Sol-Biosphere-Atmosphere (ISBA) model are used as inputs for HyMAP. Previous works showed that the use of ENVISAT data enables the reduction of the uncertainty on some of the hydrological model parameters, such as river width and depth, Manning roughness coefficient and groundwater time delay. In the context of the SWOT preparation work, the automatic calibration procedure was here applied using SWOT VM measurements in the framework of an Observing System Experiment (OSE). The synthetical data were obtained applying an instrument simulator (representing realistic SWOT errors) for one hydrological year to HYMAP simulated WSE using a "true" set of parameters. Only pixels representing rivers larger than 100 meters within the Amazon basin are considered to produce SWOT VM measurements.The automatic calibration within HyMAP had so far been performed using the MOCOM-UA multicriteria global optimization algorithm. This minimisation algorithm converges towards a Pareto front describing an ensemble of optimal parameter sets. Still, it requires a large number of model integrations and thus a high computational cost. An alternative algorithm is here proposed to reduce the cost of the optimization process : the derivative free, local and mono-objective minimisor BC-DFO is used and leads to similar results to those of MOCOM for a much reduced computational cost.

The Contribution of the Future Mission SWOT to improve Simulations of River Stages and Stream-aquifer Interactions at Regional Scale

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The main objective of this study is to provide a realistic simulation of river stage in regional river networks in order to improve the quantification of stream-aquifer exchanges and better assess the associated aquifer responses that are often impacted by the magnitude and the frequency of the river stage fluctuations. This study extends our earlier work to improve the modeling of the Seine basin with a focus on simulating the hydrodynamic behavior of the Bassée alluvial wetland, a 120 km reach of the Seine River valley located south-east of Paris. The Bassée is of major importance for the drinking-water supply of Paris and surroundings, in addition to its particular hydrodynamic behavior due to the presence of a number of gravels. In this context, the understanding of stream-aquifer interactions is required for water quantity and quality preservation. A regional distributed process-based hydro(geo)logical model, Eau-Dyssée, is used, which aims at the integrated modeling of the hydrosystem to manage the various elements involved in the quantitative and qualitative aspects of water resources. Eau-Dyssée simulates pseudo 3D flow in aquifer systems solving the diffusivity equation with a finite difference numerical scheme. River flow is simulated with a Muskingum model. In addition to the in-stream discharge, a river stage estimate is needed to calculate the water exchange at the stream-aquifer interface using the Darcy law. In this context, the future mission SWOT and its high-spatial resolution imagery can provide surface water level measurements at the regional scale that will permit to better characterize the Bassée complex hydro(geo)logical system and better assess soil water content.

At this stage, the Bassée is considered as a potential target for the framework of the AirSWOT airborne campaign in France, 2013. Keywords: SWOT, AirSWOT, River stage simulations, Stream-aquifer interactions, Regional scale , Hydrosystem modeling

Benefits of Satellite (SWOT) and Airborne (AirSWOT) Wide-swath Altimeter to Study the Garonne River

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The future Surface Water and Ocean Topography (SWOT) satellite mission, jointly developed by NASA and CNES, for a launch in 2019, will provide 2D maps of water elevations at an unprecedented resolution. The wide-swath altimeter KaRIn (Ka-band Radar Interferometer), its main payload, will observe 100 m wide and larger rivers, which is one order of magnitude better than current nadir altimeters capability. The main French rivers, such as the Garonne River in South West of France, will be observed by SWOT between two and four times, depending of the river reach location, per satellite repeat time period (i.e. 22 days). SWOT products over the continents delivered to the scientific community will be a time-dependent inventory of lakes/reservoirs distribution, their associated storage change and a global estimate of river geomorphological parameters (river network location, floodplain topography...) and variables (river width as a function of river elevation change, river slope, derived discharge...).

To prepare the SWOT mission, KaSPAR, an airborne Ka-band radar interferometer, has been designed by NASA/JPL for the AirSWOT airborne campaigns. AirSWOT will fly over the Garonne River in 2014. To plan the AirSWOT flights over the Garonne, a hydrodynamic modeling of the 50 km river reach between Tonneins and La Reole cities developed by LNHE have been used as input to an AirSWOT measurements simulator developed by JPL. The purpose of this work is to provide useful information to:

1- estimate the number of flights needed and the best time periods of the year to maximize the water level and discharge variability measurements;

2- help to design the required in-situ measurements to validate AirSWOT data and identify where they should be located to be the most efficient;

3- test the capacity to estimate discharge from SWOT/AirSWOT data using different algorithms.

In this presentation, the methodology to prepare Garonne AirSWOT campaigns along with early results will be presented.

Variationnal Data Assimilation of AirSWOT and SWOT Data into the 2D Shallow Water Model DassFlow, Method and Test Case

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For river hydraulic studies, water level measurements are fundamental information, yet they are currently mostly provided by gauging stations mostly located on the main river channel. That is why they are sparsely distributed in space and can have gaps in their time series (because of floods damages on sensors or sensors failures). These issues can be compensated by remote sensing data, which have considerably contributed to improve the observation of physical processes in hydrology and hydraulics in general and, in particular, in flood hydrodynamic. Indeed, the new generation of satellites are equipped with sensors of metric resolution. Remotely-sensed images from satellites such as SWOT (Surface Water and Ocean Topography) would give spatially distributed information on water elevations with a high accuracy (able to observe river wider than100m with a vertical precision ~dm) and periodic in time (revisiting ~week at mid-latitude).

Gathering pre-mission data over specific and varied science targets is the purpose of the AirSWOT airborne campaign in order to implement and test SWOT products retrieval algorithms. A reach of the Garonne River, downstream of Toulouse (FRANCE), is a proposed study area for AirSWOT flights. This choice is motivated by previous hydraulic and thermal studies (Larnier et al., 2010) already performed on this section of 100km reach of the river. Moreover, on this highly instrumented and studied portion of river many typical free surface flow modelling issue has been encountered, and this river reach represents the limit of SWOT observation capability.

The 2DH (vertically integrated) free surface flow model Dassflow (Honnorat et al., 2005; Honnorat et al., 2007; Honnorat et al., 2009; Hostache et al., 2010; Lai and Monnier, 2009) especially designed for variational data assimilation, will be used on this portion of the Garonne River. Mathematical methodologies such as twin experiments (Roux and Dartus, 2005; Roux and Dartus, 2006) will be performed on several modelling hypothesis in order to identify main characteristic of the river. An identification strategy would allow to retrieve spatial roughness along the main channel, variation of the local topographic slope or else temporal evolution of the streamflow.

The Impact of the Assimilation of SWOT Satellite Data into a Large Scale Hydrological Model Parametrization over the Niger Basin.

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Satellite measurements are used for hydrological investigations, especially in regions where in situ measurements are not readily available. The future Surface Water and Ocean Topography (SWOT) satellite mission will deliver maps of water surface elevation (WSE) with an unprecedented resolution and provide observation of rivers wider than 100 m and water surface areas above 250 x 250 m over continental surfaces between 78°S and 78°N. The purpose of the study presented here is to use SWOT virtual data to improve the parametrization of a large scale river routing model, typically employed for global scale applications. The method consists in applying a data assimilation approach, the Best Linear Unbiased Estimator (BLUE) algorithm, to correct certain input parameters of the ISBA-TRIP Continental Hydrologic System. In Land Surface Models (LSMs), parameters used to describe hydrological basin characteristics are generally derived from geomorphologic relationships, which is not always realistic. The study focuses on the Niger basin, a trans-boundary river, which is the main source of fresh water for all the riparian countries and where geopolitical issues restrict the exchange of hydrological data.

Here, we assume that modeling errors are only due to uncertainties in the precipitation forcing field. Since the SWOT observations are not available yet and also to assess the skills of the assimilation method, the study is carried out in the framework of an Observing System Experiment. The true precipitation field is then supposed to be known and is used to generate synthetical SWOT observations over the period 2002-2007. The satellite measurement errors are estimated thanks to an instrument simulator. The impact of the assimilation system on the Niger River modeling is estimated using various in situ and satellite measurements, such as discharge and fraction of flooded area.

Integrating Swath Altimetry with Land Surface Hydrology Models

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The planned Surface Water Ocean Topography (SWOT) satellite mission, which is projected[†] to be launched in 2019, would provide global observations of water surface elevation (WSE) at an unprecedented spatial resolution. Apart from WSE and inundated area, SWOT observations could also be used to estimate river discharge providing a novel global dataset for hydrological applications. In this study, we evaluate the estimation and integration of river discharge estimates with a land surface hydrology model. The experimental design is based on a synthetic data assimilation experiment, which starts with a baseline model simulating hydrological states and fluxes. This baseline simulation is designated as "truth", while a corrupted simulation is used as the "first-guess" emulating the expected errors in modeling the hydrology of large river basins. Water surface elevations from the "truth" simulation are fed into the SWOT Instrument Simulator to produce the satellite observations with the correct orbital and error characteristics. The synthetic observations are then merged into the "first-guess" simulation to estimate the hydrological states (e.g. soil moisture) and fluxes (e.g. runoff) as well as model parameters. The assimilation technique used is the Ensemble Kalman Smoother (EnKS) that represents model errors with an ensemble of simulations in a Monte Carlo approach. The assimilated estimates are compared with the corresponding "truth" values, and the impact of the SWOT observations to the closure of the land surface water balance is evaluated. Moreover, the improvements in the hydrologic estimates after assimilation are examined as a function of spatial scales, by partitioning the river basin into different geomorphologically informed levels.

[†]The SWOT mission has not been formally approved by NASA. The decision to proceed with the mission will not occur until the completion of the National Environmental Policy Act (NEPA) process. Material in this paper related to SWOT is for information purposes only.

Capability of SWOT to Measure Storage Change in Water Management Reservoirs

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The Surface Water and Ocean Topography (SWOT) mission will provide an unprecedented opportunity to investigate human impacts on the global water cycle. At present, in situ observations of reservoir storage globally are sporadic and highly dependent on political boundaries, and inferences from existing nadir alitimeters are limited to a few of the largest reservoirs globally. Previous studies have evaluated the projected accuracy of SWOT observations of Arctic lakes; however, the accuracy of observations of manmade reservoirs will likely differ from those of lakes in several important ways. Because many reservoirs are located in artificially flooded river valleys, they tend to be much more elongated than lakes. Also, the flooded side canyons have complex shorelines. Both of these properties imply that there will be relatively more SWOT pixels along the perimeter than within the area of the water body for reservoirs relative to lakes. This means that the classification errors along bounding pixels will have a larger impact on the water surface classification. Furthermore, many reservoirs are sited in topographically complex regions, which may be difficult to observe due to topographic layover. We use the Variable Infiltration Capacity model with the reservoir model of Haddeland, to simulate selected U.S. reservoirs for which storage/surface areas are reasonably well known from pre-dam topographic data. The reservoir model is used to generate plausible storage time series, which in turn are allowed "flood" the reservoir's bathymetry in order to generate maps of water level and surface area. These simulated surface maps are used as input to JPL's SWOT instrument simulator to generate synthetic SWOT observations, from which errors in estimated surface area and storage volume are inferred. We also utilize time series of the inferred storage and surface area from the synthetic observations to develop smoothed estimates of surface area/water level and surface area/volume relationships, and applied these relationships to the individual synthetic water level observations to determine the extent to which the smoothed relationships reduce errors in estimated surface area and volume.

Recent Progress in Development of SWOT River Discharge Algorithms

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The Surface Water and Ocean Topography (SWOT) Mission is a satellite mission under joint development by NASA and CNES. The mission will use interferometric synthetic aperture radar technology to continuously map, for the first time, water surface elevations and water surface extents in rivers, lakes, and oceans at high spatial resolutions. Among the primary goals of SWOT is the accurate retrieval of river discharge directly from SWOT measurements. Although it is central to the SWOT mission, discharge retrieval represents a substantial challenge due to uncertainties in SWOT measurements and because traditional discharge algorithms are not optimized for SWOT-like measurements. However, recent work suggests that SWOT may also have unique strengths that can be exploited to yield accurate estimates of discharge. A NASA-sponsored workshop convened June 18-20, 2012 at the University of North Carolina focused on developing SWOT-specific ways to improve discharge retrievals by leveraging spatial and multitemporal correlations in discharge-related variables such as width, depth, slope, velocity, and channel roughness. While SWOT will measure changes in depth over time, probably the most important challenge in measuring discharge is that SWOT will not measure channel bathymetry that exists below baseflow. Recent work suggests, however, that it may be possible to infer bathymetry by combining multiple SWOT observations with other available datasets. For example, because there is always a positive relationship between width and depth variations, the more precise SWOT observation (either width or changes in depth) can be used to constrain the error budget of the other variable. The goal of this paper is to present the results of the NASA workshop, including concrete algorithms as well as key future research directions necessary to develop truly robust SWOT discharge algorithms.

Fine Scale Altimetry

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Although radar altimeters have revolutionised oceanography over the last 20 years, one of their major drawbacks is that

they only take measurements directly below the satellite. One response to this has been the design of wide swath altimeters. However, with the development of small inexpensive satellites, and since the instruments are relatively cheap, an alternative is to fly a constellation of small altimeter satellites. In this paper, we describe a tool we are developing to help design altimeter constellations. Any number of satellites can be flown and the error characteristics of both the instruments and the geophysical corrections can be varied. For example, what would be the error structure of the sea surface when we give a constellation scenario of one day repeat orbit, an inclination of 80 degrees and four satellites in one plane? Another example, uses a one day repeat orbit with an inclination of 80 degrees but employing 16 satellites evenly distributed over four orbital planes. There are two main modes used in this simulation to describe the ocean surface: statistical methods to describe the ocean; and synthetic sea surfaces supplied by the UK Met Office.

We select four regions based on their different sea surface height properties. The first region is located within the Gulf Stream where there is high mesoscale activity (i.e. a strong signal). The second region is around the Azores representing low mesoscale activity, hence weak signal. The North Sea is the third region chosen because it is susceptible to storm surges. The final region is within the western Mediterranean Sea, a semi enclosed basin where strong mesoscale activity exists but the tides are small compared with the open ocean.

Mission Applications Support at NASA

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The NASA Applied Sciences Program is actively supporting an agency-wide effort to formalize a mission-level data applications approach. The program goal is to engage early-phase NASA Earth satellite mission project teams with applied science representation in the flight mission planning process. The end goal is to "to engage applications-oriented users and organizations early in the satellite mission lifecycle to enable them to envision possible applications and integrate end-user needs into satellite mission planning as a way to increase the benefits to the nation."

Two mission applications representatives for each mission, including the Surface Water and Ocean Topography (SWOT) mission are tasked with identifying and organizing the applications communities and develop and promote a process for early-phase missions to optimize the reach of existing applications efforts enhance the applications value of the missions. There is high value in project-level awareness of mission planning decisions that may increase or decrease the utility of data products to diverse user and potential user communities (communities of practice and communities of potential, respectively).

Successful strategies to enhance science and practical applications of SWOT and GRACE-FO data streams will require engaging with and facilitating between representatives in the science, societal applications, and mission planning communities. Some of the elements of this program include identifying;

- Early adopters
- Applications Team; Project Scientist, Deputy Project Scientist, Project Manager,
- Mission/products well enough to effectively incorporate all potential users

Products resulting from this effort will include; workshops, workshop summaries, web pages, listserves of interested users/scientists, Applications Plans, and participation in key meetings.

Development and Operations of Satellite Altimeter Services at EUMETSAT.

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Monitoring of the ocean is crucial to the understanding of the weather, climate, water cycle, to the monitoring of natural resources and ecosystems, as well as to our ability to mitigate natural and human-induced hazards. Satellite observations are recognised as a fundamental input for these tasks as they provide a unique, uniform coverage over the global ocean. The space component of the global ocean observing system has both developed and matured significantly over the last decades. These, now operational, interests are the core justification of EUMETSAT's involvement and growth in the field of satellite oceanography, with our specific focus on providing environmental services, due to the fact that they interact with, drive, or are driven by our main focus areas: meteorology and climate.

The main current involvement of EUMETSAT in satellite altimetry is the partnership with CNES, NOAA and NASA in the OSTM/Jason-2 mission. For Jason-2, EUMETSAT and NOAA are providing the near real time data services as required by marine meteorology, seasonal forecasting and operational oceanography. NOAA and CNES are providing data services for climate applications. In addition, EUMETSAT disseminates Jason-1 products in near real time. In the near future EUMETSAT will expand its altimetry focussed activities through its involvement in the Jason-3 (Poseidon-3), Sentinel-3 (SRAL) and SARAL (Altika) missions. Jason-3 is the continuation of the reference altimetry mission established by TOPEX, Jason 1 and OSTM/Jason 2, lead this time by the operational agencies EUMETSAT and NOAA. EUMETSAT will operate the ESA Sentinel-3 satellite and provide the marine data products. EUMETSAT will also provide near real time data services, similar to those of OSTM/Jason-2 for the SARAL mission.

Looking further into the future, EUMETSAT leads together with ESA and NOAA the continuation of the altimetry reference mission, known as the Jason Continuity of Services (Jason-CS). Current activities focus on programmatic cooperation, phase A and B studies, in order to establish a mission concept and roadmap. Seamless continuity of the reference mission beyond Jason-3 requires a Jason-CS launch around 2018.

In this presentation we will provide a general overview of the EUMETSAT altimeter based activities and we will provide information about the data products and dissemination services provided by EUMETSAT giving access to these data.

The Sentinel-3 Mission: Overview and Status

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Global Monitoring for Environment and Security (GMES) is the European programme to establish a European capacity for Earth Observation. GMES is designed to provide European policy makers and public authorities with accurate and timely information to better manage the environment, understand and mitigate the effects of climate change and ensure civil security. Sentinel-3 is an Earth observation satellite mission designed for GMES to ensure the long-term collection and operational delivery of high-quality measurements to GMES ocean, land, and atmospheric services, while contributing to the GMES, emergency and security services. Key Sentinel-3 measurement requirements, corresponding to identified user needs, have been derived from GMES and include:

- ☐ Sea surface topography (SSH), significant wave height (Hs) and surface wind speed with enhanced measurements in the coastal zone, sea ice regions and over inland rivers, their tributaries and lakes;
- ☐ Global coverage Sea surface temperature (SST) at a spatial resolution of 1 km and equivalent accuracy to ENVISAT AATSR.

- ☐ Visible, and Short-Wave Infrared radiances for oceanic, inland and coastal waters at a spatial resolution of 0.3 km, equivalent to ENVISAT MERIS with complete ocean coverage in 2-3 days.
- ☐ The Sentinel-3 mission addresses these requirements by implementing and operating:
- ☐ A dual frequency, Synthetic Aperture Radar Altimeter (SRAL) instrument supported by a dual frequency passive microwave radiometer (MWR) for wet-tropospheric correction, a Precise Orbit Determination package including a GPS receiver, a DORIS instrument and a laser retro-reflector.
- ☐ A highly sensitive Ocean and Land Colour Imager (OLCI) delivering multi-channel wide-swath optical measurements for ocean and land surfaces.
- ☐ A dual-view Sea and Land Surface Temperature Radiometer (SLSTR) delivering accurate surface ocean, land, and ice temperature.
- ☐ A collaborative ground segment providing management of the mission, management, development, production and access to core data products in an operational near real time delivery context.

The mission foresees a series of satellites, each having 7-year lifetime, over a 20-year period starting with the launch of Sentinel-3A in late 2013 and of Sentinel-3B in late 2014. During full operations two identical satellites will be maintained in the same orbit with a phase delay of 180º. This paper provides an overview of the GMES Sentinel-3 mission including the mission background and user requirements, a technical description of the space segment, a brief overview of the ground segment concept, and a summary description of Sentinel-3 data products and their anticipated performance.

Poster Session: Hydrology and Land Processes

Satellite Radar Altimetry over Land: a Global Perspective

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Satellite radar altimetry makes a key contribution to oceanographic studies, with continuous series of observations spanning more than 20 years. In addition to the ocean echo retrieval, a substantial volume of echo data has been collected over land surfaces. These echoes contain a wealth of information on surface heights of land and inland water, in addition to unique information on surface inundation, composition and roughness, and soil surface moisture.

This paper presents a global overview of multi-mission land altimetry, including global waveform analyses of data from ERS1, ERS2, EnviSat, TOPEX, Jason1, Jason2 and, as available, CryoSat2. The results showcase the land altimeter measurement capability, and demonstrate the additional information that can be retrieved. For land height determination, more than 120 million waveforms have been successfully retracked to yield height estimates from past and current altimeter missions. The results confirm the superior waveform retrieval capability over topographic surfaces of ERS1 and ERS2 compared to TOPEX, Jason1 and Jason2. This is due primarily to the wider range window of 'ice mode', as evidenced by analysis of both 'ocean mode' and 'ice mode' cycles of ERS2. The unique mode-switching capability of the EnviSat RA-2 adds further capability to retrieve echoes over land, primarily because the instrument is able to change to 20MHz mode to maintain lock on complex underlying topography, and then switch back to 80/320 MHz modes in a timely manner, to acquire more useful waveform data. The operation of this unique mode-switching capability is assessed globally, and its performance further studied using the RA-2 1800Hz Burst Echoes (BEs).

Finally, a global assessment of height retrieval from the EnviSat BEs is presented to examine the effect of the higher 1800Hz sampling rate. This, considered together with an analysis of outcomes from the CryoSat2 CRYMPS simulator, and available CryoSat2 SAR FBR data, is used to assess the enhanced retrieval potential of the Sentinel3 SRAL altimeter over land.

Soil Moisture from Satellite Radar Altimetry (SMALT)

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Soil surface moisture is a key scientific parameter; however, it is extremely difficult to measure remotely, particularly in arid and semi-arid terrain. This paper outlines the development of a novel methodology to generate soil moisture estimates in these regions from multi-mission satellite radar altimetry. Key to this approach is the development of detailed DRy EArth ModelS (DREAMS), which encapsulate the detailed and intricate surface brightness variations over the Earth's land surface, resulting from changes in surface roughness and composition. These models are created by cross-calibrating and reconciling multi-mission altimeter sigma0 measurements from ERS1, ERS2, EnviSat and Jason2. This approach is made possible because altimeters are nadir-pointing, and most of the available radar altimeter datasets are from instruments operating in Ku band. These DREAMS are complicated to build and require multiple stages of processing and manual intervention. However, this approach obviates the requirement for detailed ground truth to populate theoretical models, facilitating derivation of surface soil moisture estimates over arid regions, where detailed survey data are generally not available.

This paper presents results using the DREAMS over desert surfaces, and showcases the model outcomes over the Simpson desert, the Sahara, and the Kalahari desert. A global assessment is presented of areas where DREAMS are being generated, and an outline of the required processing to obtain soil surface moisture estimates is given. Results for altimeter derived soil moisture validation with ground truth are presented together with comparisons with other remote sensed soil estimates. First soil moisture products from ERS2 and EnviSat radar altimetry in arid regions are presented, and the temporal and spatial resolution of these data are reported.

The results generated by this ESA sponsored initiative will be made freely available to the global scientific community. First products are planned for release within the next few months. Further information can be found at http://tethys.eaprs.cse.dmu.ac.uk/SMALT.

Radar Altimetry for glacio-hydrological research on the Tibetan Plateau

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Tibetan Plateau as an elevated heat source plays an important role for the regional and global climate due to its impact on the monsoon circulation. At the same time the ecosystems of the plateau are highly vulnerable to the effects of climate change. The plateau area has an average altitude > 4000 m a.s.l. and is covered by semiarid grasslands, highly glaciated mountain ranges and numerous lakes. Most of the lakes on the plateau are endorheic i.e. they have no outlet and their volume thus reacts sensitively to changes in the hydrological cycle (glacier melt, evapotranspiration, precipitation, melt of permafrost). Recently, a lot of attention has been paid to the connection beteween glacier dynamics and lake level chnages. Radar altimetry data from spaceborne platforms such as ERS-I/II, Envisat, TOPEX/Poseidon or Jason-2 build a unique archive for the quantification of lake level changes on the Tibetan plateau for the last two decades. However, due to the relatively large footprint of traditional radar altimeters only larger lakes could be monitored. With Cryosat-2's SAR-In mode not only monitoring of smaller lakes becomes possible but also information on changes in ice thickness of mountain glaciers can be derived. Here we present results of analysis of lake level changes from different satellite radar altimeters including first results based on Cryosat-2 data.

Satellite Altimetry and Other Satellite and In Situ Observations for Monitoring Hydrological Regime of the Western Siberia

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Western Siberia is a large region with mostly flat relief, that lead to the formation of a multitude of interconnected natural objects - large and small rivers streams, large floodplains, lakes, bogs etc. . Flooded areas and bogs also act as a buffer zone, providing a dampening "sponge" effect on the water redistribution within the river system. Large area covered by rivers and wetlands results in high rate of evaporation compared to any other large boreal watershed. Northern part of the Western Siberia is located in the permafrost zone and has dynamic thermokarst processes. This zone is also influenced by human activity (construction of roads, gaz and oil pipelines etc) that affects the primary hydrological network.

We present the results of systematization and classification of landscape patterns, as well as study of variability of hydrological processes in the study region at different temporal (from multi-year to seasonal) and spatial (from local to regional) scales through a multidisciplinary approach based on in situ and remote sensing data. Radar altimetry, radiometry and optical satellite data are used in combination with the in situ observations and the recent field studies done in 2008-2011.

We present the variability of water level (from radar altimetry) and surface properties (from altimeter waveforms parameters) for the 21 mid-size watersheds of the Western Siberia (Ob' river system and Nadym, Pur and Taz rivers). Seasonal and interannual variability of water abundance is studied using radar altimetry and radiometry. We also analyse the role of the snow cover in the formation and seasonal distribution of runoff in the region of Poluy, Nadym, Pur and Taz rivers by using in situ and satellite estimates of the snow water equivalent, and present results of the hydrological numerical modelling for this region.

This research has been done in the framework of the Russian-French cooperation GDRI "CAR-WET-SIB", French ANR "CLASSIQUE" project and FP7 MONARCH-A project.

Application of the Satellite Altimetry over Terrestrial Water Body: A Case Study on Aral Sea

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Satellite altimetry has revolutionized the determination of water levels of terrestrial water bodies especially in remote areas and for poorly gauged inshore waters. One of these kinds is the Aral Sea, a receding lake located in Central Asia. In this work we demonstrate the application of combined multi-mission satellite altimetry to observe individual basins of the Aral Sea. A best possible harmonization between the different altimetry missions (Jason-1, Jason-1 extended, Jason-2, Envisat, Envisat extended, Icesat and GFO) is reached by selecting similar calibration models as far as possible, and a constant offset (range bias) is added to each mission to calibrate them relative to Topex/Posidon. In general all missions correspond well to each other quite with some slight discrepancies. Due to the large size of the lake, slight water level variations are also observed within one pass of a mission. Precise mean water levels of each basin over certain periods are computed by least square adjustment of all available altimetry measurements during this period. A digital elevation model of the Aral Sea is subsequently intersected with the water level time series of each basin to compute volume changes. Alternative, biannual lake volume time-series are computed by intersecting horizontal water masks generated from Landsat data. It is shown that volume changes from both approaches agree very well.

Global Inland Water Monitoring in Near Real Time: Current Capabilities

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Measuring the earth's river and lake resources using satellite radar altimetry offers a unique global monitoring capability, which complements the detailed measurements made by the steadily decreasing number of in-situ gauges. To exploit this unique remote monitoring capability, a global pilot scheme was implemented in 2005 to derive river and lake surface height measurements from multi-mission satellite radar altimetry.

Currently Near-Real-Time (NRT) products from the Jason-2 satellite altimeter are automatically generated based on data acquired daily from CNES; this allows for estimates of river and lake heights within 3 days of the satellite measurement. In addition to Jason-2, other altimeter missions such as Jason-1 and EnviSat, before it switched into its new 30-day orbit, have produced NRT results. Jason-1 results were initially used prior to the launch of Jason-2 in 2008. EnviSat RA-2 provided results for 1229 targets globally, with an additional 52 targets available from Jason-2. Due to the orbits of the different missions Jason-2 results from a given target are available every 10 days, compared to every 35 for EnviSat. Cumulatively these combined missions represent over 20,000 measurements spanning 9 years.

Supplementing the available NRT data are historical records and time-series. These are available for the complete EnviSat RA-2 35 day mission period and Jason-2. As the system has been in continuous operation it is possible to derive multi-mission results for a number of targets, providing users with easy access to a valuable historical reference of inland water height variation.

In addition to offering altimetry results in an easily accessible form, the system also includes the ability to deliver NRT results directly to users via email. This is particularly advantageous to users in the developing world where bandwidth is limited or at a premium.

This paper presents an overview of the current capabilities of the River and Lake Near-Real-Time system, along with examples of combined time-series over a number of targets.

The ESA River and Lake System: a User Analysis

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The ESA River and Lake system has been running as a pilot project since 2005, providing river and lake heights within 3 days of satellite overpass, using data from EnviSat, Jason1 and Jason2. Many users have subscribed to this service, with requirements encompassing water resource management, river modelling, hydroelectric power generation and siting of in-situ gauges.

Using the records from this very successful pilot scheme, a detailed analysis of River & Lake users has now been undertaken to investigate user geographic distribution and data requirements, and to assess trends among the user data. The main focus of this analysis was based on overall current users, subscribed users and subscribed targets.

Attributes that were used to conduct an analysis are as follows; for each user, the country, continent, email address and email domain (the email domain was used to determine the user country from which the request was made). The total number of countries and continents were then compared by percentage of subscribed users, and the requested targets were also analysed by country and continent.

From this analysis, it was observed that the current users of the website are widely geographically distributed. However, the majority of these users are located in European countries, with a significant proportion also from the USA. Within individual countries, users originate from a diverse range of commercial, academic and military organisations. The global analysis showed that the subscribed users occur in higher proportion from developed countries compared to developing countries. A significant number of developing countries also have subscribed users; this is particularly true for users choosing the email option, where data from subscribed targets are automatically sent to users every time new data are created. In contrast, the majority of the subscribed targets obtained from the web interface are found to be within developing countries. A global target analysis revealed that the most popular targets subscribed to with this service are within Asia.

These results for subscribed targets were unexpected as there were far fewer subscribed users from Asia compared to those from other continents. The analysis outcomes consistently indicate that most of the subscribed users that were not from Asia and Africa were interested in targets within those developing continents, emphasising the critical importance of the River and Lake service in providing key data over targets where in-situ gauge data are not available.

A Display System for Quality Assessed Inland Water Timeseries from Satellite Radar Altimetry

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The ESA River & Lake system has measured the changing heights of more than 1280 inland water targets globally. However, past and current altimeters overfly thousands of additional targets; timeseries have been generated for more than 25,000 targets from Envisat alone. Due to the large number of targets involved, an automated grading system has been devised to classify each target as good, moderate, poor or not captured, based upon a combination of statistical criteria and environmental signal assessment. This grading is now being performed on all inland water timeseries generated from a number of altimeter missions.

In order to examine the characteristics of these graded altimeter derived river and lake timeseries in the context of individual catchment basins, it was decided to create an interface to access these data in a user-friendly format. This has now been implemented in Google Earth, designed to display the results of targets from ERS-2, EnviSat, TOPEX, Jason-1 and Jason-2. The goal of this system was to facilitate identification of well captured targets and examine trends and characteristics within individual river basins, using the results of the statistical target assessment and the environmental signal detection. This paper presents the Google Earth based system, showcases individual river systems and discusses the outcomes within individual rivers of the environmental signal assessment. Continental-scale outcomes are also discussed. The results demonstrate that displaying these timeseries in geographic context provides valuable and readily accessible additional information.

Recent Developments in Hydroweb

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We present the current state of the database as well as developments in progress. HydroWeb (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/) provides offline water level time series on rivers, lakes and floodplains based on altimetry data from several satellites (Topex/Poseidon, ERS, Jason-1&2, GFO and ENVISAT).

The major developments in Hydroweb concerns automatic acquisition and processing of IGDR data for updating time series in near real time (both for lakes & rivers) and also use of additional remote sensing data, like satellite imagery allowing the calculation of lake's surfaces.

A lake data centre is under development at the LEGOS in coordination with Hydrolare Project leaded by SHI (State

Hydrological Institute of the Russian Academy of Science). It will provide the level-surface-volume variations of about 150 lakes and reservoirs, calculated through combination of various satellite images (Modis, Asar, Landsat, Cbers) and radar altimetry (Topex / Poseidon, Jason-1 & 2, GFO, Envisat, ERS2). The final objective is to propose a data centre fully based on remote sensing technique and controlled by in situ infrastructure for the Global Terrestrial Network for Lakes (GTN-L) under the supervision of WMO and GCOS.

Further additional products are planed in Hydroweb, in particular floodplains extent variations from the Modis instruments.

In a longer perspective, the Hydroweb database will integrate data from future missions (Jason-3, Altika, Sentinel-3) and finally will serve for the design of the SWOT mission. In particular the products of hydroweb will be used as imput data for simulation of the SWOT products (water height and surface variations of lakes and rivers).

Monitoring of monsoon lakes level and extent variability in middle Yangtze basin using ENVISAT and JASON2 altimetry data and MR-HR satellite images

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Long times series of satellite radar altimetry are now available for observation of large hydrological systems. In this study we measure water levels in the Middle Yangtze basin to improve knowledge of this hydrological system behaviour. For the first time, all the major monsoon lakes connected to Yangtze, ie Poyang, Dongting, Tai, Hongze, Cao lakes, water levels have been determine and monitor using ENVISAT mission and/or Jason2, over a period including the full Envisat mission (up to October 2011 orbit change) in case of Poyang lake. Concerning Dongting lake, as TOPEX/Poseidon, ENVISAT and JASON2 measurements are available, we proceed to intercomparison of water levels altimeter observations over 20 years.

In parallel, thanks to programming capability offered within the ESA MOST Dragon II project, lakes' water extent was monitored. For Poyang lake, we processed more than 730 images, mostly ENVISAT ASAR WSM and MERIS FR completed by MODIS data (from 2000 to 2002) and few Cosmo-Skymed images in 2010-11. In addition, more than 60 HR satellite images, Landsat TM, Beijing, DEIMOS, HIJ1 A-B data have been exploited over Poyang lake. For Dongting Lake, MODIS imagery acquired from 2000 to 2008 is the core data of the monitoring. A specific focus is made in 2011 exploiting Cosmo Skymed and HIJ1 A-B.

For both water height and water surfaces, correlations with gauge stations data located both on the Yangtze River and on the main lake body and its sub basins were also studied.

Results highlight the decreasing tendency of water surfaces and water height from 2002 to 2009. This decrease appears to concern as well peak of floods and water stay duration during the flooding season, as the lowering of water level during the dry season. The apparent increase of duration of this dry season is associated with very low later level and extents. The year 2010 was marked by a change in the trends, with a long period of inundation (3.5months) but framed with two very dry and long winter season. Additionally, year 2006 appears nonstandard, with an astonishing drop down of water level and extent both on Dongting and Poyang lakes. For this year 2006, taking into account the rainfall annual fluctuations, two reasons can be proposed as explanation for the observed variation scale and timing changes of the lake draw off. A global one regards El Nino effects, a lack of rainfall at regional scale, and a local one the three Gorges dam's effects, as lake's water level and surface of Dongting and Poyang Lakes are highly controlled by Yangtze River flow which is now consequence of dam functioning modes. Local water management policies of these water bodies and polders policy have a non negligible impact and would have to be investigate too.

This synergistic exploitation of data derived from Earth observation systems and in situ data will provide very valuable information for the water resource management at the scale of the middle Yangtze watershed.

Seasonal Variations in Altimetric Measurements from Envisat: Surfaces and Climate Conditions

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Altimetric measurements depend on the ability of the altimeter to predict the position of the surface below to within a narrow range. It's ability to do this is compromised by surface conditions, which vary seasonally. This poster presents a survey of the seasonal variation in data recovery over various types of terrain, using all the Envisat RA2 mission data gathered to date. Suggested causes are given.

River Water Stage by Altimetry over Ganga and Tributaries

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For past two decades, the altimeter data from various satellite missions have been used for the monitoring of the water level of ocean and other inland water bodies. It had shown a good agreement with in situ data with accuracy in order of few centimeters to measure the water stage of the rivers. Though radar altimeter data is available with repeatability of 10 days to 35 days, this is suitable enough to study the seasonal or inter annual variations. We have used the GDRs data of ICE-1 re-tracker for ENVISAT, Jason2 and Topex / Poseidon (T/P) missions from the CTOH database (http://ctoh.legos.obs/mip.fr) to compute water level variations over the Ganga River and at few locations of on its tributaries. The VALS utility based on the concept of virtual station is used to obtain the time series. The time series are calculated on all the possible virtual stations over rivers for above mentioned missions. The obtained time series of water level follow the monsoon pattern with maxima during August-September and minima during April-May. For Envisat data, the years 2003 and 2008 present the maximum water stage, for most of the cases, across the rivers. The comparison of altimeter derived data is done at one point of lower Ganga which shows a very good agreement with in situ data. These time series can be useful, after validation, in study like satellite derived discharge for monitoring the river water flow or flood analysis. Water level time series over Virtual Stations on the Ganga River from Envisat, T/P and Jason2 are now posted on site of LEGOS, Toulouse-France.

Comparison of Altimetry-derived Water Levels from Global Databases over the Amazon Basin

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Radar altimetry missions (Topex/Poseidon, Jason-1 and 2, ERS-1 and 2, ENVISAT RA-2, and GFO) provide a global and continuous monitoring of inland water bodies (i.e., lakes, reservoirs, and inland seas, rivers and floodplains)over more than twenty years. Time series of altimetry-derived water levels are obtained by difference between the altimeter range and the orbit of satellite taking into account instrumental, atmospheric and geophysical corrections when the water body is crossed by an altimeter groundtrack. The accuracy of the time-series is highly dependent on the width of the river and its environment (i.e., vegetation cover and orography). It generally varies from a few centimeters over lakes, floodplains or large rivers to a few tenths of centimeters over narrow rivers covered with a dense vegetation cover. A few data centres currently provide altimetry-derived hydrological products consisting of time series of water levels with reference to an ellipsoid or a geoid obtained as the average or the median of all the valid measurements over a specific area or altimetry station. Time series of water levels of rivers and/or lakes can be downloaded from the Hydroweb (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/), Global Reservoirs and Lakes (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/index.cfm), and ESA River and Lake (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main) websites. Here, we propose to compare the water level times series derived from ENVISAT RA-2 and Jason-2 made available by CTOH and ESA River and Lake websites to the record from the closest in situ gauge station in different locations of the Amazon basin. The accuracy of these two products will be estimated in terms of availability of the data and using classical statistical estimators: bias, RMSE and correlation.

Potential Applications of Altimetry Radar on Water Resources Management in Nile River of Sudan

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The Nile River, is the longest river in the world having a total length of about 6700 km, traversing an extremely wide band of latitude, from 4o South to 32o North. The area draining into the Nile river system of about 3 million km2 extends over ten African countries which are home and source of livelihood to approximately 180 million people. The two main river systems that feed the Nile are the White Nile, and the Blue Nile, with its sources in the Ethiopian highlands and with Tekeze-Setit-Atbara river system contributes to the flow further downstream of Khartoum in Sudan. The annual runoff potential of about 85 billion cubic meters where average annual runoff estimates varied depending upon the length of records used for the estimation. Compared to other major river basins, the Nile Basin's disparity in water availability differs sharply among sub-basins which are complex and need continuous hydrometric measurements using remote sensing data, as an alternative to in-situ hydrometeorological data. As a case study, the potential applications of altimetry radar in water level measurements and volume estimation using altimetry radar in river systems covering northern-part of Sudan was explored. Altimetry data obtained from ERS (ENVISAT) and Topex/Posiedon (T/P) missions are compared with gauge data for selected river systems. With remote sensing and GIS supported validation tools, the water level estimated with low RMSE of 0.70 and good accuracy of less than ± 2 m far to use for operational hydrology but good enough for tracking variation trend. Such altimetry radar methodology however found to be a promising and very valuable tool for monitoring water bodies such as lakes and trans-boundary river basins, like Nile thereby contributing to some confidence for decision support systems for Nile River Basin initiative being implemented by various government and non-government institutions. Such method gives some insights and picture on the accuracy of altimetry products for regional water resources management, specifically to flood hazard mitigation and water volume management. Moreover, altimetry radar data over water bodies are an innovative data source for hydrological applications. It can be used to update hydrological models in real time and can significantly enhance space-based decision support system to water resources engineers, especially in remote and poorly gauged river basins. Other future applications and capacity building on academic and applied research on the use of altimetry radar for near-real-time processing on water resources-related activities such rainfall-runoff modeling, assimilation of altimetry data, and reservoir simulation for possible collaboration and sharing of resources with concerned agencies will be explored.

4D Water Level Variations in the Amazon Basin by satellite altimetry

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A 4D -e. g. spatial and temporal- sampling of the water level variations in a basin is a major input for a large variety of applications for which in-situ data are often insufficient, such as for instance hydrological modelling forced or tuned by water level information or for near real time monitoring.

Altimetric satellites have now collected valuable measurements of water level over the great basins for two decades. In the Amazon basin where this study has been focused, several hundreds of time series have been computed; they spread over more than 30 contributors draining all the major sub-basins of the Amazon watershed. Given its natural global vertical referencing, satellite altimetry also gives access to the extent and repartition of the surface waters along the vertical axis. In this study, we present and discuss the 4D variations of the water stages obtained all over the Amazon basin by processing the data of the ENVISAT and JASON-2 missions. In particular, we show how important it is that successive satellite missions are scheduled to fly the same orbits to generate long and consistent time series. Besides, we show that making long lasting series by merging data from different missions must be conducted with great care because each mission and processing algorithm of the raw altimetry data has its own biases.

Kalman filter Approach for geophysical lake level Time Series using multi-mission Altimetry

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Since many years, satellite altimetry has been proven to be a valuable technology for monitoring inland water. In case of large lakes the ground tracks of several altimeter missions provide a favourite sampling capability with respect to space and time. However, considering distinct locations of the lake, only geophysical lake heights can be compared to each other - assuming that the lake level coincide within sub-decimetre level with an equipotential (level) surface.

We use carefully cross-calibrated altimeter missions such as Envisat, Jason-1, Jason-2, Topex, Cryosat-2, etc. and generate for the along-track observations geophysical heights by subtracting a high resolution hybrid geoid. This hybrid geoid is computed by merging the ultra-high resolution gravity field EGM2008 with the low-degree part of the latest GOCE based gravity field model. It can be shown that more consistent lake heights are obtained by using this hybrid geoid. Time series of gridded lake heights are then derived by a Kalman filter approach in order to account for the stochastic properties of the altimeter observations and for small deviations between the lake heights of different epochs.

Using lake Victoria as a case study we generate multi-mission time series of gridded lake levels and investigate the errors of the geophysical heights as well as possible causes for residual deviations of these heights from an equipotential surface. We consider in particular residual geoid errors, hydrodynamic causes, and degraded altimeter performance at the lakeshore.

Compared Variations of Argentino Lake and Brazo Rico based on Satellite Altimetry including Perito Moreno Glacier Damming Events

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Located in a mountainous area Argentino lake is one of the biggest water bodies in South America. Its well-known for extreme ice damming events due to the presence of the Perito Moreno glacier splitting the southernmost branch, known as Brazo Rico from the main body of the Lago Argentino. Although very difficult location and very narrow size of Brazo Rico branch, the altimetry data processing from Envisat mission can provide time series

of lake surface heights over both parts. Coupled with optical Landsat imaging those results give possibility to evaluate the total water storage during ice damming events and maintain the radar altimetry reputation as an invaluable source of information in hydrology sciences. The presence of two in-situ stations allow a detailled comparaison with real data and confirm excellent acuracy of altimetry over Lake Argentino and Brazo Rico branch.

All results are integraded with Lake database (Hydroweb) allowing near real time monitoring of water level and storage variations of about 150 lakes and reservoirs,freely

available on a web site.

Radar altimetry Support the Management Gauge Networks

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The hydrological observation network in the Amazon basin is made of conventional rainfall and water level stations presently maintained by the Agência Nacional de Àguas (ANA. The water level network has long been plagued by difficulties associated with spatial coverage, timely delivery and data errors. Satellite observations are important means for providing hydrologic data with acceptable spatial and temporal resolution, and radar altimeters embarked onboard successive satellites since the early 1970's collect measurements of water level over rivers in a well-defined geodetic reference frame and can be used to address some of these problems. The study period was 1993 to 2010. As result, we present examples from the Amazon basin where radar altimetry has been used to provide an independent dataset that can be used to support the management of hydrological observation networks to join new data with conventional field data.

Climatology and Climate Variability of Lake Carrera/Buenos Aires and Baker river Basin. A Combination of in situ, Satellite (Altimetry and Gravimetry) and model Data

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The study we are reporting here is related with the Lake General Carrera /Buenos Aires/Chelenko (GC/BA/C hereinafter) 46° to 47°S latitude and 71° to 73°W longitude) and Baker river basin, which is located in Patagonia on the Chilean-Argentinean border, on the Chilean Aysén region and the Argentinean province of Santa Cruz. The lake drains importantly to the Pacific Ocean on the west through the Baker River and intermittently to the east the Atlantic Ocean. The lake has a surface of 1850 km2, which makes one of the biggest lakes of South America, and greatest of Chile. Lake GC / BA / C is of tectonic-glacial origin, i.e. a result of the combined effect of glacier and tectonic movements. The action of glaciers in conjunction with intra-plate tectonic movements are caused by faults within the plates that are responsible for the formation of the Lake geomorphology. The GC/BA/C lake belong to the Baker river basin (26726 km2), which contains part of the North chilean Icefield. This hydrologic basin has gained enormous knowledge over the recent years since a hydroelectric plant is projected within the region and two dams along the Baker river. The knowledge of lake water balance and the baker basin hydrological variability is, therefore, essential.

The first aim of this presentation is to present the different stages of this work, notably the difficulties that arises through the path of this research and how space mission help substantially in deciphering the different seasonal water budget components. First insights, based mostly in in-situ data provided some information about the contribution by river input through snowmelt from the Andes could be of primary importance, though the lack of water input by ungaged rivers appeared critical. Particularly, incertitudes on the in-situ data, mostly the lack of spatial coverage, principally in precipitation and temperature, impeached any conclusion. Thus, the second aim is to show how Space gravimetry with the help of a low resolution hydrologic model help in deciphering the role played by some components of the water budget. Then associated with computation of meteorologic and hydrologic components at higher spatial resolution, which was particularly difficult, specially over the northern icefield, allowed to decipher the particular importance of the Andes snow over the river input into the Lake and on the water budget of the Baker basin.

G.M. Zambrano was funded by national CONICYT 21080378 grant (CONICYT Ph.D doctorate scolarship 21080378). This work was part of the ECOS C04U02 (Chile-France) project > continental hydrology from a combination of altimetry, gravimetry and in-situ data. Application to the Andean Region. >

Water Storage Monitoring in the Aral Sea Basin, a Transboundary Water Management Issue

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Up until the last century the Aral Sea was one of the biggest lakes in the world . It is understood that the hydrology and behaviour of the Aral Sea cannot be separated from a larger investigation on all the central Asia water management and climate conditions. The Aral Sea is located in an arid zone characterised by high amplitude of temperature between summer and winter and low precipitation throughout the year. On the Aral Sea evaporation is almost ten times higher than the precipitation; hence the role of both rivers feeding the lake (Amu Darya and Syr Darya) is essential to maintain the hydrological equilibrium of this water body. Together they provided around 60 km3/year of fresh water to the former Aral Sea. In the mid XXth century it was decided to intensively develop the agriculture of cotton and rice through irrigation. This was followed by a shrinkage of the Aral sea level from +53 meters above the 0 Baltic sea level in 1960 to +27 meters in 2010.

Presently, the drainage basin of Amu Darya and Syr Darya, is shared by 6 different countries: Uzbekistan, Kazakstan, Tadjikistan, Kirgizstan, Afganistan and Turkmenistan. It was understood that the water problems of the region thus need to take into account the whole watershed rivers and reservoirs in a frame of transboundary water management.

In the mid-nineties, a political agreement was signed between upstream and downstream countries, for a rational use of the water resources. For example for the Syr Darya river, Kirgizstan and Tadjikistan accepted to retain water in winter in large reservoirs and keep this water storage at the disposal of Kazakstan and Uzbekistan who need a large amount of water in the dry season for irrigation to agriculture activities. In compensation, the downstream countries provide gas and electricity to Kirgizstan and Tadjikistan. However such an agreement is still today contested by upstream countries who feel that they are not paid enough for their own effort. It is a source of contention among others, between these countries.

UNESCO, NATO and other international organizations redoubled their effort during the last 15 years to provide a framework to enhance the collaboration between political managers, hydrologists and scientists in general. Tools (financial and technical) are also being developed to assess water storage evolution in the whole Central Asia. Space technologies have been widely operated for this purpose. Optical and radar remote sensing have been used for analysing soils, vegetal cover evolution, desertification, agriculture, etc … while radar altimetry has opened a new mode of lake and reservoir monitoring still not largely developed but promising as demonstrated in this presentation for such a framework.

Evaluation of Multiple Satellite Altimetry Platforms for Studying Inland Water Bodies and River Floods

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Early altimetry missions were dedicated to studying ocean and ice volume and levels, however, their potential to monitoring inland water bodies such as lakes, rivers and wetlands has been more recently recognised. Depending on satellite orbit, surface water level has been measured at temporal resolutions varying from 10 to 35 days, starting from the early 1990s. For inland floods, optical satellites have gained popularity for inundation mapping, but altimetry satellite are not affected by weather condition, have a narrower footprint and may have the potential to measure river flows and provide reliable information of water stage in remote areas where gauge data is absent and in multi-channel systems where topography is complex.

This study focused on evaluating the performance of multiple altimetry satellites to measure inland water body elevation changes, but also floodplain flows for large inland rivers. Altimetry data for Lake Argyle and Lake Eildon (Australia) was validated against in-situ gauging data. Lake Argyle was selected as the main focus because it is the largest inland water body in Australia with ground orbit coverage from ICESat, ERS1&2, ENVISAT, Topex/Poseidon, Jason1 and GFO and has water elevation data since 1973. Lake Eildon has long term gauging data and a ground track from the Jason1&2, and the Thomson River/Cooper Creek near Longreach and under Jason2 was selected to analyse the potential for flood monitoring.

By overlaying ground tracks over study water bodies we selected satellite orbits using Geophysical Data Records (GDR) and obtained data from providers. BRAT (Basic Radar Altimetry Tool) was employed to analyse raw datasets and extract elevation ranges (distance from the satellites to surface of the earth). Water elevation time series were obtained by subtracting ranges from satellite altitude above reference ellipsoid and converting this ellipsoidal elevation to Australian Height Datum (AHD) using Geoid undulations from Geoscience Australia.

Our analysis of different retracking algorithms on C and Ku bands across the various altimetry platforms on Lake Argyle showed that Ku band has better agreement with gauge data in comparison with C band. Comparing different retracking algorithms of ENVISAT revealed that elevation ranges from ICE1 algorithm using Ku band showed the closest agreement with gauging data (mean 0.25 and RMSE 0.42). Comparison across all altimetry satellites showed that ICESat satellite laser altimetry provided the most accurate (under 10cm) set of water elevation measurements of the inland waters, benefits from the small footprint (50-90 m) and higher along-track resolution (40 Hz, ~170 m). The results for a flood wave moving along the Thomson River in January to April 2011was able to replicate the high flows and showed complex water surface hydrodynamic behaviour in a multi-channel system. This study has added to the body of work demonstrating that altimetry satellites have the ability to monitor terrestrial water bodies at accuracies ranging from few centimetres to tens of centimetres (depending on the satellite and used retracking method). This study also provides insight into applications for monitoring inland flood wave characteristics and hydrodynamic behaviour as has been the foundation for a new project to establish eleven sites on the Cooper-Diamantina Rivers at the location of Jason2 and ENVISAT ground tracks to further validate the capabilities for monitoring inland flooding in large river-floodplain systems.

Analysis of Envisat Individual Echoes over Inland Water

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The EnviSat altimeter during its long mission has amassed a huge database of altimeter echoes. The normal along-track sampling rate for EnviSat is 18Hz, not dissimilar to that of most previous altimeters. However, EnviSat has the added capability of providing data over the underlying surface at the full 1800Hz for one second every 3 minutes. These 'Individual Echoes' can be studied with no waveform averaging over topographic surfaces because the instrument noise is very low. Analysis of the waveform shape allows identification of areas of inland water, with small targets identifiable from only one 'clean' echo. These bursts are gathered over a wide variety of lakes, inland seas and rivers. Over smaller water bodies, the surrounding terrain often impacts the waveform shape, and these composite echoes can be identified and filtered out. These bursts are globally distributed, and the orbit of EnviSat, with only a ±1k deadband, allows for co-location of bursts over repeat cycles.

Studying the shape of an Individual Echo allows classification of the underlying surface as still water, ruffled water, land or a combination thereof. The distribution of waveform types can yield valuable information, such as showing the freeze-thaw cycle on bodies of water such as the Hudson Bay. Due to the capability to identify areas of open water from as little as one echo, analysing the number of contiguous echoes displaying open water characteristics can produce an estimation of the size of water bodies for a given region. This has been performed over a section of Eastern Europe with annual variation in the proliferation of small pools of water.

In this paper we will discuss the applications of EnviSat RA-2 Individual Echoes and the quality of the data provided by analysing this information over inland water. We will compare bursts from still water and ruffled water as well as provide examples of water surface levels that have been produced. The overall aim is to show the validity of the burst echoes with regards to inland water monitoring, to highlight the potential of the next generation of altimeters with a higher Pulse Repetition Frequency and to complement the existing altimeter datasets.

Evaluation of CryoSat-2 Measurements for the Monitoring of Large River Water Levels

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This study focuses on the accuracy assessment and the usability of CryoSat-2 measurements for the monitoring of large river water levels. CryoSat-2 satellite, launched in April 2010, was designed "to determine fluctuations in the mass Earth's major land and marine ice fields". Its main payload instrument is a radar altimeter capable of operating in three different modes including the conventional low resolution mode (5 km resolution), a SAR mode (250 m resolution) and an interferometric SAR (SARin) mode. The later mode is know to be more accurate on topographic surfaces. Thanks to SAR interferometry processing, the location of the surface elements responsible for the main echoes returned to the altimeter's antenna can be pinpointed within the global radar footprint. Off-nadir effects are then taken into account in order to better estimate surface heights.

CryoSat-2 orbit has a higher spatial resolution (7.5 km at equator) and a longer orbit period (369 days) than conventional altimeters used for inland altimetry have. From a theoretical point of view, the CryoSat-2 temporal sampling period is too long to be used to monitor river water level variations. However, since its orbit is spatially tightened, sampling becomes very rich along the rivers path. The orbit is also characterized by sub-cycle which covers consecutive tracks every 30 days and could help to improve the overall temporal resolution.

The study will focus on building spatio-temporal time series of the river water levels. This approach may involve spatio-temporal interpolation of the water levels, both along the spatial and the temporal dimensions, in order to gain maximized benefits of the 30-days sub-cycle. (This issues the same questions as when multi-mission data, acquired by two or more satellites at different places along a river path, are to be mixed.) Moreover, the CryoSat-2 data usefulness will be assessed for hydrological applications such as river slope estimation, the data will also be evaluated in the perspective of reinforcing the spatio-temporal sampling of data products built upon other "conventional" satellites. A geographical mask have been submitted and accepted by ESA in the frame of the CryoSat Data AO. It covers the main rivers of the Amazon basin between longitudes (-74.0º;-47.0º) and latitudes (-5.14º;3.08º) in which SARin mode is implemented. Note that the study will be based on the "instrument processing facility L2" product. At the time of writing, this product is being reprocessed from scratch by ESA and should be made available in spring 2012.

CryoSat-2 SARin mode and data seem really promising, the technique being uncommon for river water level monitoring as well as bringing new ways to look at hydrology from space. The study will try to illustrate the potential benefits of CryoSat-2 satellite data and give a path towards the monitoring of river water levels using it, focusing on the specificities of the instrument and its platform orbit.

On the Use of the Altimetric Virtual Gauge for Computation of River Discharge

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Satellite altimetry has the capability to provide measures of river stage (or level) from space. By utilising retracking schemes designed for inland waters, meaningful river stages can be recovered when standard techniques fail. Using these schemes gives altimetric stage data along the Mekong from ERS-2 and ENVISAT. In this study we summarise methodologies to estimate daily discharge from altimetric stage data including quality control in a number of scenarios including (1) measurements at a downstream site assuming that in-situ data available at a site upstream and (2) assuming an ungauged site using remote sensing data. For the first approach the results show that the use of the altimetric stage data (compared to the VIC hydrological model) improved the predicted discharge with the Nash-Sutcliffe r2 value increasing from 0.823 to 0.893 at tested locations. In method (2) use is made of satellite altimetry to provide a time series of river channel stage levels and longitudinal channel slope, with Landsat data used to provide a range of channel widths over a 50km reach of river. A simple method is proposed to estimate the unknown river channel bathymetric depth based on the Q90 (the discharge that is exceeded 90% of the time) value at a location on the same river. The results show r2 of 0.900 and 0.861 at two locations on the Mekong. The sensitivity of the results to shallower and deeper bathymetric depths is also considered.

A New Method to Derive River Discharge from Satellite Altimetry (ENVISAT)

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The global publicly available discharge database is limited and tends to decline. As the available discharge data does not meet the needs and requirements of the global hydrological community, alternative measuring techniques must be sought. Over the past several years satellite altimetry, have been investigated as an alternative for monitoring inland water level.

In present study, using post-processing considerations, the estimated water level time series from altimetry have been achieved for under study Rivers with average errors of 10-30 cm. Discharge measurements from a close by gauging station of altimetry footprint are investigated for possible functional relationship with water level from altimetry. This study proposes a new method to build this functional relation without the need for having them at the same time. This new method provides the opportunity of extracting updated discharge values from the altimetry data for River like Mekong which the discharge measurements are only available within periods of 1960-1970 and 1991-1994.

A stochastic process model for the time series of discharge is considered to take advantage of cyclostationarity of discharge. This model is combined with the estimated discharge from altimetry and available in-situ measurements. In fact, process model and observation model together form a linear dynamic system. The result of this system is estimated using the combination of the information from the process model and the observations. This estimation should be unbiased and have minimum variance. In this study we have used the Kalman filter to solve this dynamic system and achieve the unbiased discharge with minimum variance. A cross validation process has been performed over the estimated discharge using the Kalman filter approach. Mean Squared Errors (MSE) of 0.5-5 mm/month for estimated runoff of different rivers have been achieved using the validation of estimated discharge against the in-situ measurements.

Water Level and Discharge Estimation in part of Mahanadi River and Sunderban Delta, India Using Altimeter Data

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The monitoring of water level and river discharge is one of most important component in most of the hydrological studies and provides essential input data for flood forecasting systems. The present study has been done with Geosciences Laser Altimeter System, GLAS-ICESAT (Ice, Cloud and land Elevation Satellite) and TOPEX POSEIDON altimeter data (2003-2005) for part of the Mahanadi River and Sunderban delta in India to measure river discharge and water level. The TOPEX POSEIDON altimeter data for part of the Mahanadi River was provided by Centre of Topography of the Oceans and the Hydrosphere (CTOH) LEGOS. Similarly ICESAT product, GLA 14 was used to find the water level in Mahanadi River near Mundali barrage in Orissa state of India. The width of river was more than 250 m at the tracks of both ICESAT and TOPEX Poseidon data. The river daily river water level, discharge and rating curve was available for few points downstream and upstream of altimeter data tracks. This information along with ASTER GDEM and field survey was used to correlate altimeter derived water level with river discharge at the altimeter data locations. The average relative error between the calculated and observed discharge is 10.97% which shows that the proposed method can be used in river discharge estimation. Similarly, altimeter data was used in Sunderban delta in West Bengal state of India for monitoring the sea level changes due to tidal changes. This study shows that the space borne altimeter data can be used to monitor the inland water bodies with wide spatial extent and this technique can be applied for the upcoming SARAL (Satellite with ARGOS and AltiKa) mission of ISRO-CNES and proposed SWOT (Surface Water and Ocean Topography) mission of NASA.

Satellite Altimeter Derived Discharge of the Ganga Brahmaputra River from 1993 to 2012.

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The Ganga-Brahmaputra accounts for ~25% of the total amount of freshwater received by the Bay of Bengal. Using daily in situ river discharge data along with altimetry-derived river heights, the present study aims to produce a monthly data set of altimetry-derived Ganga-Brahmaputra River discharge at the river mouths for 1993-2012. First, we estimate the standard error of ENVISAT-derived water levels over the Ganga to be 0.26 m. Using Jason-2, the standard error is estimated to be ~0.24 m over the Ganga and ~0.14m over the Brahmaputra. These values are much smaller than the range of variability of ~7 m, and consistent with the accuracy of altimeter measurements over large rivers. We then establish rating curves between altimetry-derived water levels and in situ river discharges and show that TOPEX/Poseidon, ERS/2, ENVISAT and Jason-2 data can successfully be used to infer Ganga and Brahmaputra discharge. The mean error on the estimated daily discharge derived from altimetry ranges from ~15% (~4700 m3/s) using TOPEX/Poseidon over the Brahmaputra to ~36% (~9000 m3/s) using ERS/2 over the Ganga. Combined Ganga-Brahmaputra monthly discharges for 1993-2008 are presented, showing a mean error of ~17% (~2700 m3/s), within the range (15%-20%) of acceptable accuracy for discharge measurements. Finally, we present a basic approach to infer Ganga-Brahmaputra monthly discharge at the river mouths. The upscaled discharge exhibits a marked interannual variability with a standard deviation in excess of ~12,500 m3/s, much larger than the data set uncertainty. This new data set represents an unprecedented source of information to quantify continental freshwater forcing flux into Indian Ocean circulation models.

A Framework for Satellite Estimate of River Discharge Without in Situ Measurements

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The development of radar altimetry over rivers along the last 20 years has shown a strong potential to provide valuable information on river water level dynamics to hydrologists. The development of new sensors and satellite mission concepts such as spatial interferometry (SWOT for spatialized water level and slope measurement) or temporal interferometry (Tandem X for surface velocity measurement) opens mid-term (10-20 years) perspectives for the availability of river surface variables such as width, water level, surface slope and surface velocity. Although not as accurate as in situ measurements can be, satellite measurements would ensure exhaustive and homogeneous global coverages, and provide repetitive and near real time information on these variables. Therefore a key question arises for hydrologists. Assuming the availability of satellite measured river surface variables (width W, water level Z, surface slope Ss and surface velocity Vs), with known uncertainty levels, would it be possible to estimate river discharge without any in situ measurement, and what would be the resulting uncertainty on discharge estimate ?

We developed a method to estimate river bottom parameters (river bottom elevation Zb, bottom slope Sb, velocity profile coefficient á and Manning coefficient n) from a time series of synchronous surface variable measurements (W(ti), Z(ti), Ss(ti), Vs(ti)) (ti i=1 to N) realized at different stages along the hydrological cycle. The method relies on the forcing of equality (or minimization of deviation) between two expressions of the river discharge : velocity integration on the section and Manning head loss equation. Various criterias have been developed based on the quadratic difference between these two expressions, and minimization techniques have been tested and optimized to estimate the bathymetric parameters. The method has been implemented both on simulated data, resulting from hydraulic modelling of various river scenario (SIC flow simulator), and on real data (Amazon river). Additionnaly, the robustness of the method to surface variable uncertainty has been explored.

The method gives relevant results on simulated data and on some in situ gauging stations (Manacapuru). Other in situ gauging stations (Obidos) give inaccurate results, showing current limitations of the method, that appear to be related to rapidly changing river width and season variable Manning coefficient. The method is particularly sensitive to measurement noise on slope and surface velocity, a 5% uncertainty on these variables leading to 20% error in river discharge estimate. Further investigations are on-going to improve the method, extend its field of application and robustness, and test it on an extended number of gauging stations (Rhône river).

Simulation of River Discharge Estimates from SWOT Measurements on the Amazon Basin

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Hydrological monitoring of large and remote basins such as the Amazon Basin is a very hard and costly task when only based on in situ data. In the last decades, several studies demonstrated the usefulness of remote sensing. In particular, nadir altimetry helps improving the spatial cover of water level measurements in rivers or any open-water areas, and combined with optical or synthetic aperture radar data to allows to retrieve flooding patterns in terms of surface and volume. Large efforts were put to retrieve discharge from either nadir altimeters data or from interferometric data (SRTM), all based on the manning relationship and geometric assumptions on the river-floodplain bed. In the next decade the Surface Water and Ocean Topography (SWOT) mission based on swath mapping radar interferometer will provide continuous measurements of inland water surface elevations for rivers, lakes and wetlands with an expected spatial resolution of 100 m and a revisiting period of 22 days. In this study we evaluated the potential of SWOT data to obtain discharge in the Solimões River basin. We first generated a SWOT synthetic dataset using validated results from the MGB-IPH model combined with an instrument measurement model allowing resample MGB-IPH results. The dataset was bruited using a Gaussian distribution to generate a realistic synthetic SWOT dataset. A specific algorithm was developed to retrieve discharges from synthetic data. SWOT discharges were compared with the original MGB-IPH discharges in order to determine the SWOT accuracy. We demonstrated that SWOT permits to follow the flood pattern (in terms of water level and floodplain extension) in the Solimões River during the 2002 - 2005 period even the very low water stage in 2005 and the high water level of 2002. The accuracy of discharge estimates from SWOT synthetic data is inversely related with the width of the considered river. In sections where the mean discharge is higher than 1000 $m^3.s^{-1}$, expected error is less than 5% while it is greater than 20% for sections with a mean discharge less than 200 $m^3.s^{-1}$. In the case of the Solimões River 1 Basin, SWOT synthetic data allowed estimating discharge with an error less than 10% in 60% of the computational sections.

Estimating river Bathymetry, Roughness, and Discharge from remote sensing Measurements of river Height on the River Severn, U.K.

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The Surface Water and Ocean Topography (SWOT) satellite is a swath-mapping radar interferometer that will provide water elevations over inland water bodies and over the ocean. One of the SWOT terrestrial hydrology motivating science questions is, "What is the temporal and spatial distribution in the world's terrestrial surface water storage change and discharge?" SWOT represents a fundamentally new approach to characterizing fluvial processes, especially river discharge. However, because SWOT will observe water surface elevations, but not river bathymetric elevations, the cross-sectional flow area will only be observed above the lowest observed river depth. The remaining, unknown river depth thus presents a major risk to SWOT's capability to produce accurate river discharge estimates. The so-called SWOT hydrology "virtual mission" (VM) has explored several approaches to depth estimation, including ensemble-based data assimilation (DA) strategies. Simplistic treatment of river depth spatial variability has been a key limitation of existing VM work; put simply, geomorphology matters.

The challenge for SWOT is how to perform the inverse problem of characterizing bathymetry and river flow given SWOT water surface elevation (WSE) measurements. This task falls at the intersection of two disciplines, engineering open channel hydraulics and fluvial geomorphology. In hydraulic formulations the physical form of the channel combined with conservation of mass and momentum dictate a complex spatiotemporal response of WSE to spatial changes in river bathymetry (i.e. changes in bed slope and cross-section) and temporal changes of flow propagating downstream. DA strategies offer a numerical approach to solving the inverse problem and estimating river depth. Prior bathymetry is estimated using the best-available information, then refined by conditioning upon SWOT observations.

Here we explore the capability of estimating river bathymetry, roughness coefficient, and discharge via an inverse solution to remotely sensed river heights. The latter are obtained for four overpasses during a major flood event on the River Severn, UK. The multi-temporal observations are exploited to estimate the temporally-invariant roughness and bathymetry; these are evaluated against measurements obtained in situ and used in an operational hydraulic model. Given heights, widths, bathymetry and roughness, we use Manning's equation to estimate river discharge at discrete reaches along the 22 km length of river. Sensitivity to reach length and observation errors is explored.

Lake and Reservoir Water Level Measurements from ICESat Laser Altimetry

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Thanks to two decades of radar altimetry measurements, water levels of major lakes and reservoirs are remotely measured regularly with a precision of typically a few centimeters. Except for large water bodies, radar waveforms have usually to be reprocessed using various retracking algorithms. Because of its smaller footprint (50 to 100 meters, depending on the laser observation period) compared to radar altimeters (several kilometers), and its ability to fully capture the return waveforms, ICESat (Ice, Cloud and Land Elevation satellite) laser altimetry is suitable for the retrieval of water level variations of small inland bodies, and when water returns can be highly contaminated by land or vegetation. Using imagery (MODIS) contemporaneous with the altimetry data collections, in addition to examination of the laser waveforms, methodologies have been developed that can be used to discriminate the water returns within land regions, and allow the retrieval of accurate water level estimates. We have used these methodologies to compute water level variations from ICESat measurements for the 2003 to 2009 period for major lakes and reservoirs, and validate the time series by comparison with in-situ gauge records (when available) and radar altimetry data. We also estimate water volume variations for these inland water bodies, and compare them to high resolution mascons solutions from Gravity Recovery And Climate Experiment (GRACE) estimates.

Automatic Calibration of a Flow Routing Scheme Constrained by Radar Altimetry Data

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This paper describes and evaluates a procedure that integrates radar altimetry data into the automatic calibration of global flow routing schemes. The technique is based on the minimization of biases between water levels computed by the model and observed by the altimetric radar at virtual stations. The Hydrological Modeling and Analysis Platform (HyMAP), coupled in off-line mode with the Interactions Sol-Biosphere-Atmosphere (ISBA) land surface model (LSM), is used to simulate the surface water dynamics of the Amazon basin at a 0.25-degree spatial resolution and 3-hour time step, providing daily mean outputs. The MOCOM-UA multi-criteria global optimization algorithm is used to optimize four model parameters (baseflow time delay, Manning roughness coefficient for rivers, river width and depth), by minimizing two objective functions for the 2002-2006 period. Four calibration experiments are performed by combining water discharge observations at four gauging stations and ENVISAT radar altimetry at 16 virtual stations, in order to evaluate the potential of using radar altimetry in the automatic calibration of global flow routing schemes. One experiment is based on daily water discharge observations, other combines water discharge with altimetric data, and the other two ones are driven exclusively by radar altimetry data, at 16 and four virtual stations, depending on the experiment. The calibration process is validated against water discharge observations at five gauge stations located on the main tributaries. The main findings of this study are that the use of radar altimetry in the automatic calibration of a global flow routing scheme is feasible. Results demonstrate that reasonable parameters can be obtained by using radar altimetry in an optimization procedure with competitive computational costs. Further, the automatic calibration driven by altimetric data can reliably reproduce discharges time series and a significant improvement is noticed in simulated water levels.

Radar Altimetry for water Resources monitoring in Africa, evaluating Jason2 and ENVISAT Missions for preparing SARAL/AltiKa

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In the scope of several projects (AMESD project and SEAS Gabon project), Jason2 and ENVISAT data are proposed to substitute the scarcity of conventional data in a context of great nead for resources monitoring. The main drawback is the calibration and the validation of the data, as very few or no in situ data are available, and as field validation is extremely difficult. This is the case in the Congo basin and in the Ogoue basin. For these basins, we are transferring the methods developped in the Amazon basin, and doing some validation by 1 cross-comparison between missions, 2 validation from hydrological modeling. The methods used are discussed, the applications and their implications in preparing the SARAL/AltiKa mission are exposed.

Lake Poopo bathymetry Reconstruction to assess SWOT water mask Product Accuracy

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The Surface Water and Ocean Topography (SWOT) mission will provide map of water elevations over all continental water bodies (rivers, lakes,

reservoirs, wetlands...). The purpose of this study is to assess SWOT accuracy on water mask retrieval. This done by first computing the bathymetry for a specific lake, Lake Poopo in Bolivia, and then artificially filling it at different water level to create multiple realistic scenes with accurate shorelines. Then a SWOT simulator from JPL is run on each scenes and the water mask is computed from these measurements. Finally, an estimate of the mission performaces over small and large inland water bodies is performed by comparing these virtual SWOT water masks to the "real" ones.

Lake Poopo bathymetry is computed by combining Landsat optical images,Icesat GLAS elevations and ancillary available data. Indeed, the lack of insitu measurements and accurate topography maps is overcome by using many consecutive Landsat images each representing different inundated area. Available Landsat image database gives acces to more than 100 scenes suitables for this purpose. Under the assumption that every level change corresponds to different inundated area contour,

the evaluate contours heights can be computed from few selected Icesat elevation profiles. Resulting isolines will be used to reconstruct Poopo Lake bathymetry in the limit of existing icesat profiles. Besides, several scenes with different spatial resolution will be generated to assess SWOT accuracy on water mask retrieval.

Satellite Altimetry: A Potential Reliable Source of Information in Context of Transboundary Basin Issue

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In transboundary basins, the need to share water resources between upstream and downstream countries is problematic. A key issue is the lack of data sharing in a timely manner between upstream and downstream countries. Current and future altimetry missions can provide useful information on the dynamics of surface water. Contrary to in-situ networks, satellite measurements do not remain confined within a country, but can rather provide estimates of surface water for the entire basin with a known accuracy. Being from an independent source using the vantage of space, altimetry data can be considered unbiased by all riparian countries.

The Ganges and Brahmaputra rivers are such kind of transboundary rivers. The Ganges basin is shared between China, India, Nepal and Bangladesh, whereas the Brahmaputra is shared between China, India, Bhutan and Bangladesh. Bangladesh is the most downstream country, where both rivers join together before reaching the Bay of Bengal. More than Ninety percent of the water that flows in Bangladesh comes from upstream countries. However, as no real-time data are shared with India, the immediately upstream country, flood forecast with sufficient lead time is difficult based only on in-situ measurements within Bangladesh. Currently, Bangladesh institutions use hydrodynamic modeling to increase this lead time along with the use of modeled and satellite-based precipitation estimates. However, upstream water elevations from satellite altimetry have not yet been used in this framework. It has been shown in our work that using Topex/Poseidon measurements allows computing 5-day (10-day) water elevation forecast at the Bangladesh upstream entry points with 0.40 m (0.60 m) root mean square error. Building on this promising finding, more recent work has gauged the value of extending the forecasting potential of such altimeters at locations further downstream inside Bangladesh using a well calibrated hydrodynamic model. However, current nadir altimeter missions cannot observe the whole river basin and therefore only provide information at the intersection between their tracks and the river network where the river width is large enough. This key limitation is expected to be overcome with the planned launch of the Surface Water and Ocean Topography (SWOT) wide-swath altimetry mission in 2019. SWOT will provide a global coverage of continental river basin and provide 2D maps of water elevations for rivers wider than 100 m and water bodies whose area exceeds 250mx250m. This new type of data should be extremely valuable not only for improving water elevation forecast but also for improvement of transboundary water management. As an example, potential benefits of SWOT for the observation of reservoirs in the mountainous regions of the Indus basin, shared between Afghanistan, China, India and Pakistan, will be considered in this study.

Reconstruction of Hydrological Archives in French Guiana by Radar Altimetry, Hydrodynamic Modeling and Nonlinear Analysis of Time Series

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In 1964, 18 hydrological stations were in operation in French Guiana, some of which began operating in the 50's. They were phased out and today the water level network is totally dismantled. French environmental agencies in Cayenne are trying put some stations in operation again, but the old data will not be used in the absence of a common reference in relation to current altimetric data.

The processing of altimetric data from various sources ERS, ENVISAT, JASON2 will help complete the time series of conventional stations for which there is an overlap in time and no great distance between the conventional station and the virtual station. In cases where the virtual and conventional stations are not closeby, a model of flux propagation will be used to account for the phase shift between the two stations. Finally, for stations stopped for too long for existing a time overlap between the two data sets, nonlinear analysis algorithms will be implemented to reconstruct the of missing data, propagating data from another station on the same river stream.

The feasability and result quality of this study will be very promising for numerous similar situations all around the world, especially in the African great basins like the Congo basin.

Poster Session: Marine Geodesy, Gravity, Bathymetry, and Mean Sea Surface

Error Covariance of Mean Dynamic Topography in Inverse Ocean Models

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Estimates of Mean Dynamic Topography (MDT) from satellite data provide valuable information for the oceanic surface circulation. In the assimilation of MDT data into inverse ocean models, the inverse MDT error covariance matrix is used as a weighting matrix in the optimization.

Until recently, the MDT error covariance matrix could not be determined and thus was approximated by a diagonal matrix. Now, an estimate of the full error covariance matrix is available for a MDT determined from Jason-1, GRACE and GOCE data in the North Atlantic region. This MDT and its error covariance were assimilated into the Inverse Finite Element Ocean Model (IFEOM) for the North Atlantic. The MDT error covariances, although small compared to the variances, have a large impact on the ocean model result.

The largest impact is not due to the additional weights of the off-diagonal terms in the error covariance, but due to their influence on the diagonal of the inverted error covariance matrix: The diagonal weights are increased by the error covariances by order 700 %. The available MDT error covariance estimate could not be used in IFEOM without introducing an additional "downweighting" factor. This factor was computed exclusively from the ocean model optimization theory. However, it coincides with the increase of the diagonal weights by the error covariances. For the highest degree spherical harmonics, a stochastic approach must be applied to the modelling of the MDT error covariance structure. The detailed choice of the stochastic model for the omission error turns out to be crucial for the final estimate.

The oceanic circulation of the optimized model result is modified largely in dependence of the MDT error covariance estimate. When the weighting factor is chosen carefully, the resulting ocean current structure, the meridional overturning circulation and meridional heat transports are improved by the new MDT and its error covariance estimate.

Sea Level Anomaly and Dynamic Ocean Topography Analytical Covariance Functions in the Mediterranean Sea from ENVISAT data

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The determination, monitoring and understanding of sea level change at various spatial and temporal scales have been the focus of many studies during the past decades. The advent of satellite altimetry and the multitude of unprecedented in accuracy and resolution observations that it offers allowed precise determinations of sea level variations. The realization of the GRACE mission and the development of global geopotential models form GOCE observables offer new opportunities for the estimation of sea level trends at regional and global scales and the identification of seasonal signals. In such studies, even though the data combination and processing strategies have been carried out carefully with proper control, a point that has been given little attention is error propagation through analytical data variance-covariance matrices. The latter is of significant importance in heterogeneous data combination studies since error propagation can provide reliable estimates of the output signal error. This is especially evident in the optimal estimator used in physical geodesy, i.e., least-squares collocation (LSC), where the full variance-covariance matrices are needed for the input data and signals to be predicted. When the aim is the determination of sea level variations or the dynamic ocean topography from a combination of altimetric and GRACE/GOCE observations, one can determine analytical covariance functions for the disturbing potential, its second order derivatives and geoid heights through one of the standard models, as, e.g., that of Tscherning and Rapp. On the other hand, no analytical models are available for altimetric sea level anomalies making their incorporation in LSC-based combination schemes problematic. This work presents some new ideas and results on the determination of analytical covariance functions and subsequently full variance-covariance matrices for the sea level anomalies in the Mediterranean Sea. The focus is based on single-mission altimetry data from ENVISAT for the entire duration of the satellite mission (2002-2011). For the latter, the signal and error characteristics of the sea level anomalies have been studied at monthly, seasonal and annual scales. The estimation of the analytical covariance functions is performed using 2nd and 3rd order Markov models as well as a kernel similar to that of the disturbing potential a.k.a. dependent on a series of Legendre polynomials. The same analysis has been carried out for the RioMed dynamic ocean topography model available for the entire Mediterranean in order to come to some conclusions on its spectral characteristics based on empirically derived properties such as the variance and correlation length.

Gral: An Altimetric Mission Low-cost for Providing Ocean Gravity Models

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The purpose of this paper concerns the satellite altimetry applied to the Solid Earth. It deals with the interest of a new altimetry mission, GRAL, to improve the knowledge of the short wavelengths of the gravity field. If since the sixties, shipboard gravity measurements are made on the oceans, knowledge of the oceanic gravity field has been improved since the advent of satellite altimetry.

Global models of mean sea surface or its derived quantities (gravity, topography...) have been much exploited and enabled an increase of geophysical research on the Oceans. However, they do not meet all needs and remain confined to the interpretation of medium and large wavelengths (roughly up to 20 km). The limitations of these models are first due to the radar technology, limiting the use of measurements near the coast and the spatial resolution along-track satellite (imprinting effect of about 7 km). Secondly, the measurement strategy adopted for altimetry missions generally responds more to the needs of oceanographic knowledge (temporal variability) that to the needs of a oceanic full spatial coverage.

An article in EOS Transaction American Geophysical Union by the GRAL Team [a], made an assessment of needs and prospected altimetry missions, then discussed alternative suitable missions as GRAL concept, a little formation of several conventional nadir altimeters flying closely on the same orbit, [b] and [a], and SWOT concept, a single satellite equipped with a wide swath interferometric altimeter. This last concept has then emerged as a possible response to the needs expressed by interesting community of Geophysics when NASA and CNES decided to implement such a mission (launch currently planned in 2019).

The paper aims at describing the GRAL mission concept, the associated payloads and satellites, and expected measurement performances, which can be a less expensive first guess to a high-resolution geoid. Its results combined with those of the GOCE gravity field would improve the knowledge of the short wavelengths of the mean sea surface and hence an approximation of the geoid and global bathymetry of the ocean.

[a] Louis G, Lequentrec-Lalancette MF, Royer JY, Geli L, Maia M, 2010, Ocean gravity models from future satellite missions, EOS Transactions American Geophysical Union, V91,3.

[b] Richard J, Enjolras V, Rys L, Vallon J, Nann L, Escudier P, 2008, Space altimetry from nano-satellites: payload feasibility, missions and system performances, IGARSS'08, Boston, USA.

Method to Modeling the Error of Marine Geoid Height Models

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For twenty years, the satellite altimetry missions have allowed to improve the knowledge of the gravity field over the oceans. However, the resolution of the global gravity models is limited by the capabilities of altimetry to return the short wavelengths (below 20 km). However, it is possible to locally improve the resolution of these models by including high frequency information from marine gravity measurements and from free air anomaly models derived from bathymetry which are estimated by neural networks méthods presented during the previous symposium in 2006 [Lequentrec-Lalancette et al, 2006]. This poster presents a methodology to model the true error of a geoid height model computed from gravity data deduced from altimetric missions and from precise marine gravity data. The enrichment method is based on the respective use of an estimation method by collocation method and the resolution of the Stokes formula, first, to compute a free air gravity anomaly model and secondly to deduce the associated geoid height model . The error is estimated from the error of the enhanced gravity anomaly model which is propagated by Stokes formula to the geoid height model.

There are two kinds of errors :

- ☐ Error in areas which are enriched in marine gravity measurments : it is estimated by a cross-validation method based on the collocation process
- ☐ Error in areas without marine gravity measurment : It is estimated on different roughness provinces from the gravity anomaly model derived from altimetry. The roughness of the gravity signal is computed by a method defined by Dreher [2000] from an improvement of Fox and Hayes méthodology [1985]. The delimitation of three characteristic gravity provinces is done by thresholding of the roughness computed in the wavelength lower than 50 km. In each province, the error is estimated by the differences between the free air gravity anomaly model and the marine gravity measurements available in the province.

This methodology will be described with an example of marine geoid height computed from EGM08 in a North Atlantic area which is characterized by various structural zones (ridge, margin area, ..). Then, the results will be compared with the estimated errors of the EGM2008 model [Pavlis et al., 2008].

Data and Products for Oceanography from ESA's Gravity Mission GOCE.

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GOCE, the Gravity Field and Steady-State Ocean Circulation Explorer, is ESA's Mission for building a global, high spatial resolution map of Earth's Gravity Field. Flying at very low altitude and kept in free-fall through a sophisticated drag-free control to best sense the Gravity gradients, it has been collecting data since its launch, on March 2009.

To date, three successive generations of Gravity solutions, the "Geoid", have been released, the latest on November 07 2011, based on the data available between November 2009 to June 2011.

This paper presents all GOCE available data, the format, content, and the software available for processing. The plans and the expected performances of the next releases are also discussed.

On the Incorporation of Sea Surface Topography Models in a Geoid-based Vertical Datum

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The North American geodetic communities are moving towards formally establishing national/regional geoid-based vertical datums. In this paper, an optimal adjustment strategy for incorporating sea surface topography models in a geoid-based vertical datum (for Canada and the USA) is presented. The latest official regional gravimetric geoid models are used along with the national networks of tide gauge records to estimate a W_0 value that can be referred to for vertical datum applications. The tide gauge data is incorporated along with relevant sea surface topography models obtained from combining tide gauge, satellite altimetry (used for validation offshore) and GOCE observations in order to obtain a local equipotential surface value at each tide gauge station location. These locally determined W_0 values are then used in an optimal weighted least-squares adjustment with inner constraints to obtain a geoid surface.

A Global Mean Ocean Circulation Estimation using GOCE Gravity Models

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The Gravity and steady state Ocean Circulation Explorer (GOCE) satellite mission measures Earth's gravity field with an unprecedented accuracy at short spatial scales. Preliminary results have already demonstrated a significant advance in our ability to determine the ocean's general circulation. The improved gravity model provided by the GOCE mission has enhanced the resolution and sharpened the boundaries of those features compared with earlier satellite only solutions. In this study, more recent gravity models from GOCE are combined with the DTU10MSS mean sea surface to construct a global mean dynamic topography (MDT) model. Calculation of the geostrophic surface currents from the MDT reveals improvements for all of the ocean's major current systems. Furthermore, the finer scale features, such as eddies, meanders and branches of the current system are visible.

Regional variations in mean sea level as mapped by satellite altimetry may also provide information about changes in the surface geostrophic mean circulation. Changes in the geostrophic ocean currents will have an impact on both the volume and the heat transport in the oceans which, in turn, will have an impact on the local environment and climate. A preliminary analysis of such effects has been carried out using the GOCE MDT. One example is the increasing sea level south of Greenland which signals a slow down in the North Atlantic sub-polar gyre. The results of this preliminary analysis, further demonstrate the potential of the GOCE mission in Earth sciences.

Combined Global Gravity Models including Satellite Altimetry Data

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So far three releases of GOCE-only gravity field models applying the time-wise method have been computed in the frame of the ESA project "GOCE High-Level Processing Facility". They have been complemented by satellite-only combination models generated by the GOCO ("Gravity Observation Combination") consortium. In order to further improve the spatial resolution, this satellite information has to be complemented by terrestrial gravity field data over land, and gravity information derived from satellite altimetry over the oceans. The combination is performed by addition of full normal equations for all data types, and the normal equation system is solved rigorously.

This contribution concentrates on the generation of such high-resolution combined gravity field models, with special emphasis on the inclusion of satellite altimetry. One of the main issues is the optimum relative weighting of the individual data types, requiring to stochastically model the errors of all components as realistically as possible. Concerning gravity field information from satellite altimetry, we use the compilation of mean gravity anomaly grids of DTU10 over the ocean areas. The corresponding error information in terms of standard deviations for all grid blocks is fully exploited as stochastic model in the frame of assembling and solution of the normal equation systems. In this way, this error information is propagated to the final combined gravity field models. This shall be demonstrated on the example of a full degree/order 600 combined gravity field solution.

Error Budget Analysis of a Mean Dynamic Topography

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Knowledge of the overall error budget and accuracy of a Mean Dynamic Topography and subsequently derived Geostrophic Velocities is important information for ocean studies.

Following the basic Equation MDT = MSS - N with the Mean Dynamic Topography (MDT), a Mean Sea Surface (MSS) and the Geoid Height (N), one can clearly see that the MDT is composed of two entities derived from different measurement types and hence different error budgets. They can be considered as uncorrelated as they are in our case derived by different and independent techniques. The Error Budget of the MDT has therefore two contributions, the Geoid error and the MSS error. They both simply sum up to the overall MDT error.

The investigations are based on the statistical analysis of the full covariance information provided from a GOCE geoid and the error information from an existing MSS. The core part of the analysis represents the stochastic modeling of the MDT computation and therefore the propagation of the variance-covariance information to an MDT error estimate. Special attention will be drawn to the effects of the filtering applied to the MSS and geoid heights in order to ensure spectral consistency between the two entities.

This analysis will allow quantifying the respective contributions of the two MDT ingredients to the overall MDT error and its derivatives like geostrophic velocities.

Validating predicted Bathymetry: An Approach using Two-dimensional Coherence between Altimetric Gravity and Multibeam Bathymetry

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In situ ocean depth measurements made by ships carrying echosounders cover only a few percent of the global ocean. Global models of ocean depth rely on satellite altimetry to fill the gaps. Altimeter data are processed to yield sea surface gravity anomaly maps. The gravity maps are then converted to depth maps by spectral projection techniques exploiting the correlation between gravity variations and depth variations, and calibrated to fit the available in situ data.

When this altimetric bathymetry technique was developed (Smith and Sandwell, Journal of Geophysical Research, 1994; Science, 1997) the available in situ data were insufficient to permit empirical development of a spectral projection filter. Therefore a simple Wiener optimization theory was used, employing educated guesses about the expected signals in bathymetry and signal-to-noise ratios in altimetric gravity, both as functions of wavenumber. If correct, this approach should minimize the mean square error in altimetrically estimated bathymetry.

It is now possible to test the performance of the Smith and Sandwell filter design directly, as there are now some areas of ocean floor that are sufficiently covered by detailed multibeam acoustic bathymetry surveys. We compiled acoustic bathymetry and co-registered altimetric gravity data in 25 map areas covering various tectonic regimes throughout the world's oceans. The size of each mapped area is large enough to permit estimation of azimuthally-averaged cross-spectral coherency between altimetry and bathymetry over the range of spatial wavenumbers used by Smith and Sandwell (about 10 to 160 km wavelength). We find that the simple spectral projection used by Smith and Sandwell does an excellent job of capturing the waveband where altimetry and bathymetry may be correlated.

GOCE Data Quality and Instruments Performance

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ESA's Gravity Field and Ocean Circulation Mission, GOCE, is in orbit since March 2009, systematically collecting gravity gradients from space. Its two main instruments are the Gradiometer and the Satellite-to-Satellite Tracking Instrument (GPS). GOCE, currently on its Extended Mission phase, is planned to fly through the end of 2013.

The official Level-1b and Level-2 data products provided by ESA, are systematically processed with the highest-fidelity algorithms. This paper details the current quality assesment of GOCE data, its processing algorithms and Instruments performance.

The DTU 2010 MSS and MDT Models - Recent Development in the Arctic

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Satellite altimetry can be used to derive an offshore vertical reference surface for offshore GPS navigation as satellite altimetry and GPS are conveniently given in the same reference frame. This way satellite altimetry can be used to provide a harmonized global vertical reference surface. One of the state of the art altimetric mean sea surfaces is called DTU10MSS along with its associated mean dynamic topography called DTU10MDT. The DTU10MSS surface has been derived from the physically observed time-averaged height of the ocean's surface derived from a total of 8 different satellites and a total of 8 different satellite missions like i.e., the T/P, ERS, ENVISAT and ICESAT. The base for the calculation is a 17 year joint mean profile from TOPEX/Jason-1/Jason-2.

In the presentation focus will be made on the Arctic Ocean which, due to the presence of sea-Ice is notoriously the most difficult region to model the Mean sea surface from satellite altimetry. Here the data from the new SIRAL sensor onboard Cryosat-2 can be used both to augment the mean sea surface, but also to evaluate the accuracy of the existing mean sea surfaces. In particularly Cryosat-2 offers a factor of 20 improvements in along track resolution and improved precision in sea surface height measurements.

DTU10MSS is currently the only mean sea surface that offers "true" global marine coverage. Consequently, this model is suitable for referencing the new Cryosat-2 data as this MSS covers the entire Arctic Ocean. With the near-polar inclination of Cryosat-2 this satellite provides data closer to the Pole than any other satellite altimeters. A comparison of L2 products for LRM, SAR and SAR-in data are carried out with re-tracked L1 data for the same data types.

Towards DTU2012 Global Marine Gravity Field

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DTU Space, DENMARK

Since the release of the DTU2010 global marine gravity field in 2010 the launch of several new satellites like the Cryosat-2 satellite and the GOCE satellites offers new data to the geodetic and oceanographic community.

A number of geophysical phenomena in the open ocean are still unresolved by conventional 1 Hz altimetry, but could be observed through the potential improvements offered by SAR, or Delay-Doppler (DD), altimetry onboard Cryosat. Since the geodetic mission of ERS-1 in 1994 and GEOSAT in 1985-1986 no satelite have provided data with groundtrack spacing adequate for marine geodesy. With the launch of Cryosat and its 369 day repeat and 7 km ground track spacing at the equator this has changed.

We have investigated the use of 18 month of Cryosat LRM data as well as Cryosat SAR and SAR-in data for deriving a new draft global marine gravity field map. Of particularly interests is the 369 days repeat offered by Cryosat-2 which provides denser coverage than even the ERS-1 geodetic mission data set. The first results based on the NOAA retracked and Cryosat LRM based data still do not seem to provide the expected improvement in global marine gravity field which is related to the relative high signal to noise still seen in these available versions of the Cryosat data.

Steric Sea Level Changes Using Altimetry and Gravimetry Satellites - A Case Study over Nordic Seas

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Sea level rises and falls as the temperature and salinity of the water column varies, which is known as steric sea level. The combination of satellite altimetry with the ocean mass change observations from the satellite gravity mission offers a superior method for estimating the steric sea level changes over using altimetry alone, or in situ observations of temperature and salinity from the profiling floats to be used in the Argo float program. Steric sea level changes are estimated over the Nordic Seas using ENVISAT altimetry and GRACE gravity data. The Nordic Seas is the common name for the Greenland, Iceland and Norwegian Seas. The region is bounded by the Arctic Ocean to the north, the deep North Atlantic Ocean to the south, and the shallow North Sea to the southeast.

We have used altimetry data from the ENVISAT during October 2002 to October 2010, cycles 10 to 93, and the GRACE level 2 RL04 data released by GFZ processing center during August 2002 to December 2010. It should be noted that some months are missing for the GRACE data set. Correction terms are applied to properly combine the altimetry and GRACE data, including the inverted barometer term, dynamic ocean and atmospheric terms and GRACE coefficients with degrees 0, 1, and 2 (with order 0).

The mean ocean mass change, the sea level anomalies and the variability of steric sea level over the Nordic Seas during October 2002 to October 2010 are derived. It should be noted that the mean tracks of altimetry data in the sea ice areas have large standard deviations. Because of the presence of sea ice in the Nordic seas (such as in the East-Greenland Current, the Greenland Sea and in the Fram Strait), we used the mean tracks with the standard deviation less than 50 cm in the sea ice area and therefore the coastal areas of Greenland are masked. The results show that the variations of the steric sea level change over the Nordic Seas during the mentioned period have alternating sign which depends on the salinity and temperature changes. In most parts of the Nordic seas, the annual variations of steric sea level are between 0 and 4 cm.

Gravity of the Arctic Ocean from Satellite Altimetry: Recent History and Status Report

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Five spaceborne altimeters have been profiling the sea surface topography, slope and geopotential anomalies of the Arctic Ocean beginning with the launch in July 1991 of ERS-1 and its single-frequency radar altimeter. Four subsequent, near-polar satellite altimeters include 3 more radar altimeter spacecraft: ESA's ERS-2, Envisat (RA-2 - operating now for over 10 years), and most recently, ESA's CryoSat launched April 2010. The fifth of these satellites is NASA'S ICESat which used the Geoscience Laser Altimeter System (GLAS) to profile the Arctic from 2003-2009. Over the past 20 years these five altimeters, collectively, have yielded a dramatic improvement in our understanding of the gravity, mean sea surface, and tectonic structure of the Arctic Basin - a more dramatic improvement than that obtained for any other of world' s ocean basins. Over polar seas these altimeters measure the instantaneous sea surface height at leads (openings) in the pack ice, and over open ocean. To reduce contamination by ice-freeboard signal and tracker noise, a careful retracking of the radar waveform or similar reprocessing of the GLAS data is necesssarily performed. After undergoing such reprocessing Envisat data spanning six years (2002-2008) as well as ICESat data spanning 5.5 years (2003-2009) were used in combination to construct a new Arctic ICEn mean sea surface (MSS) [Farrell et al., 2012]. This MSS has important applications for Arctic oceanography, e.g., determination of the pan-Arctic mean dynamic topography (MDT). We have used these same reprocessed Envisat and ICESat data, in the form of along-track, sea surface slopes, to estimate a new detailed altimetric marine gravity field, the ARCtic Satellite-only (ARCS-2) field, north to 86oN. No surface gravity data are used in computing ARCS-2. The long-wavelength (> 300 km) component of ARCS-2 is obtained from the new GRACE/GOCE satellite-only models (GOCO01S). Thus ARCS-2 is derived exclusively from satellite data and is independent of surface gravity observations. By adding ICESat data, we extend ARCS-2 up to 86N - farther north than previous altimetric (e.g., Envisat) marine gravity fields. ARCS-2 improves, by a factor of 2, the spatial resolution over existing marine gravity fields in many areas of the high Arctic. ARCS-2 is also used to underpin Arctic altimetric gravity fields now being computed using CryoSat-2 data. The new level of detail in the ARCS-2 field aids in tracing tectonic fabric - e.g. extinct plate boundaries - over large areas of the Arctic basin whose tectonic origin is obscured due to sea ice and sediments. Incorporation of CryoSat data into altimetric gravity of the Arctic Ocean will reveal even more tectonic detail. Airborne gravity collected during recent NASA Arctic IceBridge campaigns is used to validate models such as ARCS-2 or EGM2008 and to corroborate that errors in geoid models (EGM2008) are large (> 0.4 m) in several areas of the high Arctic.

Simulation of SWOT Data from Marine Geoid Models

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For twenty years, one answer to the oceanographic needs has been the satellite altimetry technology. The improvement of sensors and acquisition techniques has allowed gradually to increase the spatial and temporal covers as well as data accuracy. Altimetry has also answered the question of the oceanic gravity models and the global gravity field model EGM08 has been computed on the oceans from free air anomaly models estimating from satellite altimetry [a].

The SWOT mission, now planned for 2020 (?) by the NASA and the CNES, has been designed to fulfill the needs of both hydrological and oceanographic communities. It will offer a swath observation of both ocean, coastal and continental waters and their interactions due to a Ka-band radar interferometer (Karin). The data after ground treatment, would lead to a resolution and a precision better than any altimetric mission data reached until now. The small-scale process could be observed for the first time by satellite altimetry, given that the goal of the mission is to provide SSH measurements every 2 km2 for each swath on the ocean. That is to achieve a spatial resolution of 50m2 on the rivers and 1km2 on the continental reservoirs. The expected accuracy for the mission is 10 cm on water heights and 1 ìrad / 5 km on the slopes. And this aim reaches the expectations of the missions proposed by the geophysicists to improve models of the gravity field. The ABYSS project (Altimetric Bathymetry from Surface Slopes) [b], proposed by Raney et al., and the GRAL project (GRavimetrie par Altimétrie Haute Resolution; [c,d]. To quantify the interest of this mission for the Solid Earth by the knowledge of the geoid, the gravity field and in fine, to a lesser extent, bathymetry, we will simulate SWOT acquisitions from marine geoid and mean sea surface models in the North Atlantic [e]. Models of free air anomaly will then be calculated from these simulations. The comparison with existing models in North Atlantic will be realized. The contribution of the SWOT mission will be analyzed on different geodynamic deep structures and in coastal areas.

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[c] Louis G, Louis G, Lequentrec-Lalancette MF, Royer JY, Rouxel D, Geli L, Maïa M, 2010, Ocean Gravity Models from future satellite missions, EOS, Vol 91, No3, 19 january 2010.

[d] - Lequentrec-Lalancette M.F., D. Rouxel and O. Sarzeaud,, 2006, Satellite altimetry and marine gravity: toward a consistent knowledge of the gravity field, in Proceedings of the ESA Symposium 15 Years of Progress in Radar Altimetry, Venice, 12-18 march

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Mean Dynamical Topography and its Impact on Ocean Circulation Estimates in Southern Ocean

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Southern Ocean is only partially observed with altimetric measurements and very sparsly observed with in situ data that are limited to specialized deep drifters and the CTD measurements mostly along hydrographic sections. In this work we construct a first estimate of the global dynamical ocean topography from altimetric measurements and satellite only gravity models that combine GRACE and GOCE gravity data. This estimate is then assimilated into a finite element ocean model using a ensemble Kalman filter method. The result is a dynamical ocean topography consistent with ocean dynamics and close to observations.

The impacts of assimilating the geodetic information into the finite element model are assessed for Southern Ocean. The location of Southern Ocean fronts based on the criteria specified in Orsi et al. 1995 are compared to the front locations obtained from in situ data of Orsi et al. It is shown that the ocean model representation of the locations of fronts is improved by assimilating dynamical ocean topography data. Further we compare the results of assimilation outside the area covered by altimetry in the Southern Ocean. For this we use temperature of surface drifters or deep temperatures in the Weddell Sea area at 800 m depth derived from Argo composite as well as transport values along few WOCE sections.

To What Extent are Altimetry Residuals Explained by Mass Redistribution and Steric Changes?

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In order to retrieve absolute dynamic topography, an altimetric measurement is commonly reduced by a static gravityfield. In reality, the geoid will display (long wavelength) variations over time, caused by the changing mass distribution in the terrestrial hydrosphere, cryosphere, ocean and atmosphere.

In this study, we compute a joint inversion using data from GRACE and Altimetry, to solve for basin-wide mass changes occurring in Greenland, Antarctica and on land. In addition, we estimate time varying steric components over the ocean. Within the inversion, each basin will come with a predefined geoid pattern, computed from a normalized basin-load. The factors belonging to these patterns are then estimated from the inversion.

In this presentation, we apply the forward problem, to reduce the altimetric measurements with the inversion results. We investigate the resulting residuals in the space, time and spectral domain, and identify regions which show a significant change in signal.

Poster Session: Integrated Systems – Applications – Forecast - Assimilation

Large Scale Estimates of the three Oceanic Carbon Pumps

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The efficiency of the ocean in sequestrating CO2 is often quantified by the air-sea CO2 flux (the "solubility pump") or the flux of sinking organic carbon at the base of the euphoric layer (the "biological" pump).

Much less is known on the spatio-temporal variations of the "physical" pump, which implies the formation of water masses at the surface and their subsequent subduction: in a recent study focused on the region of subpolar mode water formation of the North East Atlantic (Karleskind et al., 2011), it has been suggested that the physical pump is two order of magnitude larger than both the biological and solubility pumps. In this work, we examine and compare the strength of the solubility pump (air-sea CO2 flux), the biological pump (sinking organic carbon flux) and the physical pump (carbon subduction) at the global scale. This is done by combining satellite observations (Altimetry, SST, Ocean Color and Wind stress), ARGO data (for Mixed-layer depth), climatologies (GLODAP and SOCCAT for DIC and pCO2) and results from a biogeochemical Ocean General Circulation Model (ORCA2/PISCES).

Surface Chlorophyll Responses to Eastern and Central Pacific El Niño Events Using a Multi-Satellite Analysis

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Recent analyses show the existence of a Central Pacific type of El Niño (CPEN) with a sea surface temperature warming pattern distinct from that of the "classical" Eastern Pacific El Niño (EPEN). In this study, we analyze the surface chlorophyll signature of El Niño-Southern Oscillation (ENSO) using satellite measurements (surface chlorophyll, sea level anomaly, wind, SST) and satellite-derived surface currents.

An Agglomerative Hierarchical Clustering (AHC) applied to monthly maps of satellite-derived chlorophyll anomalies between September 1997 and December 2010 allows identifying five typical ENSO structures. The first structure describes the lonely 1997-1998 EPEN of the period, the second and third represent La Niña, the fourth illustrates an "intermediate recovery period", and the fifth characterizes CPEN.

During the 1997-1998 EPEN, a large eastward shift of the oligotrophic warm pool, a deep nutrient pool (elevated SLA) and a reduction of equatorial upwelling result in negative chlorophyll anomalies east of 170°E between 10°S and 10°N (upper panel).

During the four CPEN events (2002-2003, 2004-2005, 2006-2007, and 2009-2010), the negative chlorophyll anomaly pattern has an arrow shape (lower panel). The head would be the core of the largest negative anomaly located at the equator around 170°E. Thin bands of negative chlorophyll anomaly stretches from the anomaly core along 8-10°N to the Central American coast, while another of lower magnitude extends to the Marquesas Islands at 140°W, 10°S. The tail of the arrow would be the narrow band of moderate negative anomaly along the equator from the anomaly core to the American coast. Eastward advection of the oligotrophic waters of the warm pool in the western basin combined to westward surface current in the central basin contribute to the confinement of the negative chlorophyll anomalies between 160°E and 160°W in the equatorial band. This negative anomaly core corresponds to a region of elevated SLA indicating deep nutrient (nitrate and iron) sources. Yet, this deep vertical structure is probably a second order factor on surface chlorophyll changes compared to the impact of advection. Negative chlorophyll anomalies that extend eastward from the equatorial anomaly core probably result from reduced upward iron fluxes linked to the deepening of the Equatorial Undercurrent. Away from the equatorial band, negative chlorophyll anomaly strips follow the position of enhanced eastward countercurrents.

Surface Chlorophyll-a Distribution in the Southwestern Atlantic due to Mesoscale Eddies

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Eddies play a key role in promoting the growth of phytoplankton and in the large-scale redistribution of chlorophyll-a. In this study we combine satellite altimetry and surface chlorophyll to study their co-variability within mesoscale eddies. The study is focused in the western South Atlantic between (35°S-52°S, 62°W-35°W). The western South Atlantic presents a wide range of eddy energy (e.g. 10^2 to 2x10^3 cm^2/s^2) and sharp contrasts in chlorophyll concentration (0.05 to 10 mg/m^3) and is therefore a useful region to test the role of eddies in different environments. Eddies are detected applying a modified Okubo-Weiss method to satellite altimetry data for the period 1997-2010. The satellite derived surface chlorophyll-a distribution associated with the eddy field is studied for the same period of time. On average chlorophyll-a concentrations increase (decrease) toward the center of cyclonic (anticyclonic) eddies. North of 45°S this behavior holds in regions of low and high eddy-kinetic energy. South of 45°S, surface chlorophyll-a concentrations are higher within the cores of anticyclonic eddies than within cyclonic eddies. Mechanisms to explain the above observations are discussed. The rate of cyclonic eddy-induced chlorophyll-a to the total concentration estimated as a function of location shows that up to 30% of the total chlorophyll-a may be associated to the cyclonic eddies.

Singular Value Decomposition of Ocean Surface Chlorophyll and Sea Level Anomalies in the Gulf of Cadiz (SW Iberian Peninsula)

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This study analyzes the spatio-temporal variability of satellite surface chlorophyll-a data (CHL) and Sea Level Anomaly (SLA) from altimetry data in order to characterize the influence of the regional circulation on the phytoplankton biomass in the Gulf of Cadiz (Southwestern coast of the Iberian Peninsula). The ocean color data were obtained from merging data from three sensors: Sea-viewing Wide Field of view Sensor (SeaWiFS), Moderate Imaging Spectrometer (MODIS) and Medium Resolution Imaging Spectrometer Instrument (MERIS) The AVISO weekly maps of SLA data have been reprocessed to obtain a higher spatial and temporal resolution (1/16° and daily, respectively) to improve the water circulation analysis in the basin. A singular value decomposition (SVD) analysis was performed to determine the coupled modes of variability of satellite surface CHL and SLA data for the Gulf during a 12-year period (1998-2009). We have found that the two leading SVD modes represent more than 98% of the total squared covariance. The first mode (explaining 91% of the covariance between CHL and SLA) was associated with the annual chlorophyll bloom and the annual cycle of the mean sea level. However, the second mode (explaining 6.5% of the covariance between CHL and SLA) represented the bimodal (winter and summer) circulation patterns in the basin described previously, and its interaction with the chlorophyll-a variability in the different dynamical regions such as Capes San Vicente, Santa Maria and Trafalgar, where upwelling, eddies, and fronts are found. Therefore, results confirm that the phytoplankton in the basin is very tightly controlled by meteorological and physical processes.

Some Results of dynamic Features studying in the Baltic Proper and Black Seas

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Sea Surface Temperature (SST) data and Sea Surface Height Anomaly (SSHA) are used synergistically to obtain information about mesoscale eddies, fronts and meanders, current speeds and direction in the Baltic and Black Seas.

Using RA-2 to calculate the SSHA, different areas were investigated for the studying sea eddies. Ocean colour data add information about eddies in images of chlorophyll concentration, suspended sediments and dissolved organic matter.

Information obtained is used for the eddies types classification and studying sea surface dynamics in the Baltic Proper and Eastern part of the Black Sea.

Impacts of Physical Data Assimilation on the Integration of Biogeochemistry into Mercator Océan operational systems

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The integration of marine biogeochemistry to operational systems is a timely development within the context of international initiatives focused on carbon monitoring and accounting, as well as science-based management of marine ecosystems and resources.

The objective of Green Mercator (Mercator-Vert project) is to implement a marine biogeochemical and ecosystem component at the global scale into MERCATOR operational systems. The global configuration of the state-of-the-art multi-nutrient and multi-plankton biogeochemical model PISCES has been successfully integrated to operational Mercator Océan systems.

In order to evaluate the impacts of physical data assimilation on modeled biogeochemical tracer distributions, two simulations were carried out: (i) a biogeochemical simulation forced by a physical free run (without physical data assimilation) and (ii) a biogeochemical simulation forced by a physical reanalysis (with physical data assimilation). We present a first evaluation of the capability of GREEN MERCATOR models to reproduce large scale distributions of biogeochemical tracers. To this end model output is compared to climatologies and data from one time series stations. The comparison of simulated biogeochemical fields provides a first assessment of impacts of physical data assimilation on modeled biogeochemical tracer distributions.

Can Altimetry Inform Marine Ecology?

De Monte, Silvia[1]; d'Ovidio, Francesco[2]; Lévy, Marina[2]; Cotté, Cedric[3]; Alvain, Severine[4]; Weimerskirsch, Henri[5]
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Monitoring marine ecosystems is becoming an increasingly urgent need face to the harsh exploitation of marine resources and to the anthropization of oceanic habitats, and provides key information for the development of climate change scenarios. More and more often, remote sensing is used in monitoring programs along with in situ observations: phytoplankton distribution and primary productivity are obtained by ocean colour measures, and geolocalization allows to track marine animals in their displacements.

Ecologically-relevant parameters derived by analysing such data have been recently shown to be related to the physics of the ocean surface, and in particular to the fronts of horizontal transport. The localization of such fronts and the quantification of their variability essentially relies on the resolution and coverage of altimetric measures. Langrangian reanalysis of altimetry-derived surface currents indeed reveals the fluid dynamical landscape that underlies ecological processes.

Here, I will present two instances of the coupling between ecology and ocean physics.

When combined with ocean color derived observations of dominant phytoplanktonic types (PHYSAT re-analysis), horizontal transport fronts obtained from satellite altimetry are shown to create a fluid dynamical landscape of niches that structures phytoplankton communities at the meso- and submeso- scale. Top levels of the trophic chain respond as well to transport features, and in particular seabirds colocalize with Lagrangian coherent structures. The concomitant use of nonlinear reanalysis of altimetric data, of satellite measures of wind intensity, and of seabirds 3-D position allowed us to pinpoint changes in frigatebirds behaviour over filaments. This study opens new perspectives to the use of high-resolution remote sensing in the study of the ecological mechanisms shaping the marine biota distribution.

Joint uses of Satellite/in-situ Observations and Drakkar Ocean Models: Atmospheric Forcing and Model Assessment.

Penduff, Thierry[1]; Juza, Mélanie[2]; Brodeau, Laurent[3]; Barnier, Bernard[1]; Treguier, Anne-Marie[4]; Molines, Jean-Marc[1]
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The DRAKKAR European consortium is developing, in coordination with the operational community, a hierarchy of ocean/sea-ice models (based on NEMO), and producing series of coordinated 50-year global simulations for scientific research. The OST/ST SSINOC research project contributes to DRAKKAR through joint uses of simulations and (altimeter, satellite, in-situ) observations: research on atmospheric forcing, multi-model/multi-observation quantitative assessments, Observing System Simulation Experiments, and process-oriented studies.

This poster presents two SSINOC/DRAKKAR efforts based on such simulation/observation synergies: [i] design and improvement of 50-year globally-balanced forcing functions for global ocean simulations, based on atmospheric reanalyses and satellite observations; [2] joint use of AVISO, Argo, and current meter observations for the comparative/quantitative assessment of multiple global simulations. Series of 20/50-year global simulations at increasing resolution (from 2° to 1/12°) are collocated on these observations and quantitatively evaluated with a particular focus on interannual timescales. This study quantifies the benefits of increasing resolution for climate simulations, and highlights various complementarities between observational and numerical oceanography.

Extreme Events and Statistical Structure of Sea-level Variability: AVISO vs Multi-resolution DRAKKAR Simulations

Penduff, Thierry[1]; Juza, Mélanie[1]; Sura, Philip[2]
[1]CNRS-LEGI, FRANCE; [2]FSU - EOAS, UNITED STATES

The DRAKKAR Consortium has performed an ensemble of global, multi-decadal ocean/sea-ice simulations that mostly differ by their horizontal resolution (2°, 1°, 1/2°, 1/4°, 1/12°). These simulations are first collocated at the spatial and temporal resolution of the AVISO altimeter SLA dataset, then quantitatively compared to AVISO and among themselves with respect to the first four statistical moments of SLA (mean, variance, skewness and kurtosis), in three frequency ranges.

We precisely quantify in this study how increased model resolution progressively improves the magnitude and geographical patterns of simulated mean flows, mesoscale activities and large-scale interannual variabilities. Based on a statistical mechanics theory, we extend this observation/multi-model global comparison to the distribution and statistical structure of extreme events (skewness and kurtosis of SLA distributions), and to the dynamical relationships between the latter 2 statistical moments. Beyond this multi-moment assessment of our simulations, our results raise open questions about the ocean dynamics, and the contribution of multiplicative noise in numerical simulations.

Mesoscale Variability in the Subtropical Salinity Maxima

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In situ data from the northern extension of the PIRATA array indicates the presence of significant mesoscale variability on the southern edge of the north Atlantic subtropical salinity maximum. Surprisingly, this variability is apparent in salinity, but not as evident in temperature records. We use AVISO sea level, AQUARIUS sea surface salinity, in combination with ocean eddy-resolving model to describe this variability and quantify its impact on salinity budget of subtropical salinity maxima.

Data Quality Assessment of in situ and Altimeter Observations through Two-way Intercomparison Methods

Guinehut, Stephanie; Ablain, Michael; Rio, Marie-Helene; Valladeau, Guillaume; Legeais, Jean-Francois; Larnicol, Gilles
CLS, FRANCE

Intercomparison methods also called multi-observations CalVal (Calibration/Validation) methods are widely used between in situ and satellite data to assess the quality of the latest. The stability of the different altimeter missions is, for example, commonly assessed by comparing altimeter sea surface height measurements with those from arrays of independent tide gauges [Mitchum, 2000; Valladeau et al., 2012]. Other examples include the validation of altimeter velocity products with drifting buoys observations provided by the Global Drifter Program (GDP) [Bonjean and Lagerloef, 2002; Pascual et al., 2009] that are also used for the systematic validation of satellite SST thanks to their in situ surface temperature measurements. In turn, comparison of in situ and altimeter data can also provide an indication of the quality of the in situ measurements [Guinehut et al., 2009; Rio et al, 2012].

This talk presents an overview of the two-way intercomparison activities performed at CLS for both space and in situ observation agencies and why this activity is a required step to obtain accurate and homogenous data sets that can then be used together for climate studies or in assimilation/validation tools. We first describe the work performed in the frame of the SALP program to assess the stability of altimeter missions through SSH comparisons with tide gauges (GLOSS/CLIVAR network). Then, we show how the SSH comparison between the Argo array and altimeter time series allows the detection of drifts or jumps in altimeter

(SALP program) but also for some Argo floats (Ifremer/Coriolis center). Lastly, we describe how the combine use of altimeter and wind observations helps the detection of drog loss of surface drifting buoys (GDP network) and allow the computation of a correction term for wind slippage.

Circulation and Cross-Shelf Exchanges over the Shelves of Southern South America

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We describe a suite of model simulations investigating the interaction between the large-scale circulation and the shelf circulation in southern South America. Our study area encompasses the eastern boundary system of the South Pacific and the western boundary system of the South Atlantic. Our simulations includes highly idealized, process oriented experiments that investigate the dynamical mechanisms connecting the deep ocean to the shelf, as well as realistic simulations of the Argentinean, Brazilian and Chilean shelves that are directly compared with altimeter and in-situ observations.

On The Nature Of Buoyancy-Driven Interannual Tropical Sea Level Changes

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It is commonly held that spatial patterns of interannual tropical sea level variability mainly represent the ocean's direct response to momentum input from winds. This paradigm is based partly on modeling studies of wind-driven sea level changes along the tropical Pacific. However, since the effects of buoyancy forcing on sea level are usually ignored, such a view may overemphasize the importance of the winds. To consider the influence of surface buoyancy exchanges on interannual sea level patterns, we make use of a dynamically consistent, data-constrained ocean general circulation model solution, produced by the ECCO ("Estimating the Circulation and Climate of the Ocean") group. Through a set of numerical experiments, we separate the influences of momentum input by winds and buoyancy input by air-sea fluxes of heat and freshwater. In all tropical oceans, buoyancy-driven sea level anomalies are evident, exhibiting a nonlocal character that is made manifest in westward propagating features, which tend to occur alongside propagating sea level anomalies of opposite sign driven by the winds. Such behavior suggests that the forcing mechanisms could be collocated and potentially coupled locally. In-depth consideration of closed steric height budgets reveals that the buoyancy-driven sea level changes represent the combined action of both local atmospheric forcing as well as dynamic ocean transports—mainly density advection by ocean currents. Thus, our results demonstrate that accurate modeling of interannual changes in regional sea level requires explicit consideration of the dynamical effects of surface buoyancy exchanges.

Mean full-depth Circulation in the northern North Atlantic in the 2000s derived from satellite Altimetry and repeat Hydrography

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A mean state of the full-depth summer circulation in the Atlantic Ocean in the region in between Cape Farewell (Greenland), Scotland and the Greenland-Scotland Ridge (GSR) is assessed by combining 2002–2008 yearly hydrographic measurements at 59.5°N, mean dynamic topography, satellite altimetry data and available estimates of the Atlantic–Nordic Seas exchange. The mean absolute transports by the upper-ocean, mid-depth and deep currents and the Meridional Overturning Circulation (MOCσ=16.5±2.2 Sv, at σ_0=27.55) at 59.5°N are quantified in the density space. Inter-basin and diapycnal volume fluxes in between the 59.5°N section and the GSR are then estimated from a box model. The dominant components of the meridional exchange across 59.5°N are the North Atlantic Current (NAC, 15.5±0.8 Sv, σ_0<27.55) east of the Reykjanes Ridge, the northward Irminger Current (IC, 12.0±3.0 Sv) and southward Western Boundary Current (WBC, 32.1±5.9 Sv) in the Irminger Sea and the deep water export from the northern Iceland Basin (3.7±0.8 Sv, σ_0>27.80). About 60% (12.7±1.4 Sv) of waters carried in the MOCσ upper limb (σ_0<27.55) by the NAC/IC across 59.5°N (21.1±1.0 Sv) recirculates westwards south of the GSR and feeds the WBC. 80% (10.2±1.7 Sv) of the recirculating NAC/IC-derived upper-ocean waters gains density of σ_0>27.55 and contributes to the MOCσ lower limb. Accordingly, the contribution of light-to-dense water conversion south of the GSR (~10 Sv) to the MOCσ lower limb at 59.5°N is one and a half times larger than the contribution of dense water production in the Nordic Seas (~6 Sv).

Surface and Subsurface Current Velocity from Satellite Altimetry and Hydrography in the North Atlantic Ocean

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Although satellite altimetry has relatively short data spans, the availability of concurrent multi-mission altimeters and in situ hydrography data (Argo) allows measurements to characterize general ocean circulation and its transport, for example, potentially provides insights into the evolution of Kushiro current or the Atlantic Meridional Overturning Circulation (AMOC). During the last two decades, significant rapid sea-ice thinning, increased discharge from Canadian Arctic rivers from permafrost degradation, and Greenland Ice-Sheet ablation has resulted in increased ocean freshening, postulated the potential weakening in the transport of the AMOC. Here, the study focuses on the use of contemporary multi-mission radar altimetry, GRACE, and in situ MBT/XBT/Argo to compute the surface velocities, subsurface (down to 2000 m) velocities and the transport in the North Atlantic Ocean using different approaches. The estimated current velocities are validated using in situ mooring drifters or Acoustic Doppler Current Profilers (ADCP), and used to study the evolution of the AMOC.

Steric Sea-level Variations in the Gulf of Cadiz Computed from Combined Databases

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Long time series of gridded multi-mission altimetry data (AVISO maps of sea level anomalies: 'upd' products) have been analyzed to investigate the sea level seasonal variability in the Gulf of Cadiz. Different methodologies have been used to quantify the contribution of the steric effect to the mean sea level seasonal cycle. Monthly means of temperature and salinity profiles from the NCEP Global Ocean Data Assimilation System (GODAS) were employed to calculate the open ocean steric effect over the basin, obtaining that the percentage of explained variance diminished towards the coast. When combining a high resolution climatology with satellite sea surface temperature time series better results were obtained in terms of explained variance, highlighting the importance of using high resolution temperature and salinity databases. The steric-corrected mean sea level seasonal cycle seems to indicate that sea level responds better to local steric changes rather than to steric changes in a basin wide area. This also stresses that the steric effect is mainly driven by the thermal expansion of the water column due to gain and loss of heat by the upper layer of the ocean (thermo-steric component).

Understanding the Annual Cycle in Sea Surface Height.

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The Argo Program, now into its 9th year of global subsurface ocean coverage, has grown from a sparse global array of about 1000 profiling floats in early 2004 to more than 3500 floats today. The lengthening combined time-series of Argo and altimetry grows in value as it approaches a decade of over-lapping coverage. Here we focus on the annual cycle, demonstrating that subsurface steric variability explains a large fraction of the annual cycle in sea surface height (SSH). This is now shown with unprecedented spatial resolution and accuracy on a global basis. Improvements in steric annual cycle estimation are most significant in the southern hemisphere. Steric variability includes both surface layer changes due to air-sea buoyancy fluxes, and subsurface changes due to ocean dynamics. The latter can result from either vertical or horizontal displacements of isopycnal surfaces. Argo profiles extend to depths as great as 2000 m. The depth-dependence of annual isopycnal displacement provides a basis for estimating the vertical scale of the annual cycle, even at locations where it exceeds 2000 m. This allows an estimate of the magnitude of annual steric height variability below 2000 m. Thermosteric as well as halosteric variability is considered. In the surface layers, this variability reveals heat and freshwater exchanges , as well as the signatures of water mass formation processes. In deeper layers, it helps to resolve ambiguities in subsurface horizontal versus vertical displacements. Finally, on large spatial scales we investigate how much of the difference between SSH and steric height is explained by mass-related annual variability in GRACE data, and hence how well the SSH annual cycle budget closes.

Investigating the Global Water Cycle Using Salinity Budget

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Earth and Space Research, UNITED STATES

Salinity trend is an ocean indicator of the water cycle. For example, the strengthening of the hydrological cycle in the past fifty years is accompanied by the salinification of the subtropical gyres and the freshening of tropical rainfall regions. The annual rainfall and evaporation freshwater exchange between the ocean and atmosphere contribute more than three-fourth of the global water cycle, and also dominates the global salinity pattern. In this study, we perform a trial salinity budget analysis and estimate the upper ocean and atmospheric freshwater budgets, and the gaps between them. The results show that the horizontal advection and the mixing processes can be nearly equal importance to balancing the freshwater flux in certain regions. For instance, the horizontal advection is significant in the tropics related to the strong currents, and the vertical mixing is negligible over the western boundary currents. The hydrological budget helps us understand how the ocean responds to the water cycle.

Currently, several months of Aquarius salinity measurements are available. Together with Ocean Surface Current Analyses Real-time (OSCAR) currents derived from altimetry measurements, we calculate the global salt advection and notice that the results are similar to those calculated from Argo but with more detailed structures. The seasonal variations of salinity are relatively small compared to the latitudinal variations. However, by the time of the conference we will have one full year global salinity data with which to observe and understand the seasonal changes in salt advection.

MyOcean Eddy-permitting Global Ocean Reanalysis Product: Description and Results

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We present here the global ocean reanalysis effort carried out within theMyOcean project, a contribution to the EU funded FP7 GMES Program whose goal is to set up an integrated capacity for ocean monitoring and forecasting in Europe. The production of eddy-permitting global ocean reanalyses spanning the altimetric era (1993-present) is one of the tasks of the Global Monitoring and Forecasting Centre of MyOcean.

Several partners (namely Mercator Océan, CLS, CMCC, ESSC-Readingthe and LEGI-CNRS) have produced and made available to the community several global ocean state estimations at eddy-permitting resolution covering the 1993-present period. The reanalysis production has been coordinated within MyOcean project with other Work Packages like Thematic Assembly Centres which provide the dedicated delayed time reprocessed observation data sets of SLA, in situ observations and SST for global ocean reanalyses. There are also tight links with the Cal/Val working group defining the appropriate way to assess and measure the quality of MyOcean products.

MyOcean reanalyses consist of 5 data sets. One data set (CLS) is an estimation of the ocean state based on observations only (SST, SLA and in situ profiles). The four other products use the global ORCA025 model configuration of the NEMO3 ocean/sea-ice GCM (at the eddy permitting resolution of 1/4°). All modelled products are forced with atmospheric surface variables from the ECMWF ERA-INTERIM atmospheric reanalysis. The LEGI-CNRS product is the control simulation with no data assimilation. Mercator Océan, CMCC and ESSC reanalyses assimilate various types of observations (SLA, SST and in situ hydrographic observations) using different data assimilation schemes (SEEK filter, 3D-VAR and OI).

The 5 reanalyses have been produced and are part of the MyOcean products (freely available upon request through the MyOcean web portal). The reanalyses have been assessed using a common validation protocol based on MERSEA/GODAE recommendations (CLASS 1 to 4 metrics), CLIVAR-GSOP reanalysis diagnostics and the MyOcean operational validation plan, adapted for global reanalyses.

We present here the methodology and validation framework used in MyOcean global ocean reanalyses. Then results from the different reanalysis data sets are shown results for the period from 1993 to present. By comparing the results from the different reanalysis data sets, robust features and weaknesses of the reanalyses are brought to light. Validation of the re-analyses using specific protocols and user-oriented assessment will continue during MyOcean2 with the goal to facilitate and encourage the use of these products for different applications.

Sea Level Estimates of the ECCO Central Production

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The Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) has established the ECCO Central Production solution as an ongoing global multi-decade estimate of the physical state of the ocean. The ECCO estimate synthesizes nearly complete data for the physical state of the global ocean since 1992 with a state-of-the-art ocean general circulation model. The results are characterized by their physical and statistical consistencies and are particularly suited for investigating mechanisms of ocean circulation changes and their causal relationships. A companion study ("Understanding decadal changes in regional sea level patterns and their causes in a data-constrained ocean general circulation model" by Piecuch and Ponte) examines processes underlying sea level change of an earlier ECCO solution. Here, the latest solution of the ECCO Central Production will be described with a focus on its estimation process and its estimated sea level change in comparison to observations.

The ECCO estimate is being extended in time to present on a regular basis and expanded in scope by incorporating new observations, advancements in ocean modeling, and new methods in estimation. The new observations include updated versions of in situ and satellite measurements, incorporating most recent data and quality controls, and new measurement types such as time-varying satellite ocean mass observations and global mean sea level variations. Model improvements include use of an active sea-ice model and bulk formulae for air-sea fluxes. The Central Production solution is obtained by the adjoint method, with the optimization achieved through adjustments to a variety of control variables (e.g., atmospheric state, initial conditions of temperature, salinity, sea level, etc), with near-real time extensions using an approximate Kalman filter and smoother. Additional improvements to the Central Production effort are underway to advance the fidelity and scope of the estimates. In particular, future estimates will employ a truly global grid that includes the Arctic Ocean, use of higher spatial grid resolution, and a mass instead of volume conserving formulation.

Regional High Resolution Reanalysis Covered European North East Shelf

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Mercator Océan has developed a regional forecasting system at 1/12° resolution over the North East Atlantic (IBI: Iberia, Biscay and Irish), taking advantage of the recent developments in NEMO. The model was forced by ERA-interim products (every 3 hours) including the atmospheric pressure. In addition to atmospheric forcing, the model includes astronomical tidal forcing. This regional forecasting system uses boundary conditions from the Mercator Océan global reanalysis (GLORYS: GLobal Ocean ReanalYses and Simulations).The assimilation component of the Mercator Océan system, is based on a reduced-order Kalman filter (the SEEK or Singular Extended Evolutive Kalman filter). An IAU method (Incremental Analysis Updates) is used to apply the increments in the system. The error statistics are represented in a sub-space spanned by a small number of dominant 3D error directions. A 3D-Var scheme corrects for the slowly evolving large-scale biases in temperature and salinity. The data assimilation system allows to constrain the model in a multivariate way with Sea Surface Temperature (AVHRR + Multi-satellite High resolution), together with all available satellite Sea Level Anomalies, and with in situ observations from the CORA-03 data base, including ARGO floats temperature and salinity measurements. The background SLA field accounts for the high frequency signal determined by the model and the forcing by atmospheric pressure.This reanalysis covers the period from January 2002 to December 2009.

In this presentation, the results obtained with this reanalysis system (1/12°) are compared to the GLORYS ones. A special focus will be made on the gain thanks to the higher resolution of the model and higher resolution of the SST and SLA (along tracks) assimilated in this reanalysis.

Use of ECMWF and Mercator Reanalyses for Decadal Prediction Systems Initialisation

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Climate prediction at interannual to decadal time scales is mainly an initial value problem. Furthermore, the memory of the climate system lies mostly in the ocean. Therefore, the initialisation of coupled models is a crucial point for the quality of such predictions, which are of high interest both for the society and for climate change assessment, as shown by the IPCC/CMIP5 exercise.

In this poster, we show a series of sensitivity initialisation experiments with the APREGE-NEMO CM5 coupled model, developed at CNRM and CERFACS, covering the two decades of the altimetry era. We investigate the influence of different sets of reanalysed ocean states on the initialisation system, including ECMWF reanalyses based on a coarse resolution model, and MERCATOR reanalyses based on an eddy permitting version of the same model. These experiments involve a full field initialisation method, and an anomaly initialisation method, in coupled mode, and several experiments in forced mode. Reanalysed estimates of upper ocean heat content are the test bench used in these sensitivity experiments.

Observation Sensitivity Studies at Mercator Océan: a Contribution to GODAE OceanView

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[1]Mercator Océan, FRANCE; [2]Météo France, FRANCE; [3]CLS, FRANCE

To estimate how much ocean analyses and forecasts are reliable and confident is an important issue for ocean forecasting centres. This is closely related to the observation network and to the different data types that are assimilated which have different impacts on the ocean analysis. Characterization of the sensitivity of ocean analyses to the assimilated aobservation is a central activity of GODAE OceanView Observing System Evaluation Task Team (OSE-TT, https://www.godae-oceanview.org/science/task-teams/observing-system-evaluation-tt-oseval-tt/) and Mercator Océan is contributing in several ways to this issue. Two approaches are used to assess the impact of different types of observation on the analysis error.

(i) Recently, GODAE OceanView OSE-TT has defined a framework to carry out in a coordinated way near real time observing system experiments (NRT OSEs). The objective is that different operational forecasting centres quantify the impact of each observation type during the year. More specifically, different kind of data types (e.g. SLA, SST, Argo profiles, etc...) are with-held during a particular month in a forecasting system running in parallel to the operational one. This should provide answers to the following questions. What is the sensitivity of forecasting systems to a particular observation type? How complementary are observations assimilated in ocean prediction systems? How robust are these results with respect to the different forecasting systems?

(ii) Using the adjoint method, it is possible to study how a given type of observation can help controlling the different ocean variables and regions. We focus on the SST and altimetry misfit sensitivity in the Mercator 1/4° global ocean reanalysis. Because the surface forcing is also a possible contribution to the forecast error, the sensitivity to heat fluxes is investigated.

The results of those different sensitivity studies are presented and discussed.

Quarterly Ocean VAlidation DISplay (QUOVADIS): a Quarterly Scientific Quality Bulletin for Mercator Océan Operational Systems.

Desportes, Charles; Drévillon, Marie; Régnier, Charly
Mercator Océan, FRANCE

Following the spirit of the numerical weather forecast centres quality reports, Mercator Océan publishes a quarterly bulletin: the Quarterly Ocean VAlidation DISplay (QUOVADIS). In the framework of the European project GMES/MyOcean, it measures and keeps track of the performance of the monitoring and forecasting operational systems in order to identify possible improvements. This includes measuring the impact of changes in the real time observation network and giving useful information for the improvement of this network. A second aim is to be a basis for regular interactions with the scientific community and other users so that they can derive the level of confidence for the use of the products.

Diagnostics are displayed for the global 1/12° (PSY4), global 1/4° (PSY3), the Atlantic and Mediterranean zoom at 1/12° (PSY2) monitoring and forecasting systems currently producing daily 3D temperature, salinity and current and ice products. Two new systems are operational since July 2011: IBI on the North East Atlantic at 1/36° horizontal resolution that includes the modelling of tides, and BIOMER, a global biogeochemical model at 1° horizontal resolution forced with PSY3V3R1. This bulletin provides a summary of the quality control of the input data (through collaboration with data centres). It gives a summary of real time products quality and data assimilation performance. Comparisons are maid with altimetric and insitu observations (like Argo profilers) and with independent data (tide gauges, ocean colour, etc.), over ocean and ice. It also provides forecast error statistics. It gives information on the climatic conditions (large scale atmospheric forcing or coupling).

This bulletin eventually includes process studies, assessment of the impact of altimetric data, intercomparisons of systems based on current R&D work at Mercator Océan.

New Altimeter Products for Model Assessment and Data Assimilation

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In two decades satellite altimetry has become a major component of operational oceanographic forecasting systems as it provides direct observations of meso-scale (nearly 100 km) fronts and eddies, very valuable both for model assessment and assimilation.

At the beginning Sea Level Anomalies (SLA) averaged and interpolated onto regular grids were used for assimilation. Nowadays, more and more ocean monitoring and forecasting centers have developed methods to benefit directly from along-track SLA products. As models strive for realism, they tend to reproduce higher-resolution oceanic processes using smaller grid-spacing and more realistic forcing.

Accordingly, the conception of new altimeter products more suitable to modeling needs - both coastal and global - was initiated through several European and French projects (MERSEA, ECOOP, SLOOP, PISTACH, COASTALT, MYOCEAN) in the past few years.

In particular, the "Tailored Altimetric Products for Assimilation Systems" (TAPAS) initiative was launched in 2010 by the MYOCEAN Sea Level Thematic Assembly Center (SL TAC). The objective of this initiative is to develop and maintain a dynamic collaboration between SL TAC and Monitoring and Forecasting Centers (MFC) for defining new sea level products that better answer data assimilation needs.

At the present time, the TAPAS initiative has led to the development of specific along-track SLA products that were distributed to the MFCs for carrying out impact studies. Compared to the classical AVISO along-track SLA products, the main modifications concern:

- The shorter length of the along-track filter to extract shorter scale signal from the altimeter data.
- The possibility for the users to remove some/all geophysical corrections applied on the SLA (tides, inverse barometer, high frequency dynamical atmospheric signal…) to better fit the physics of their model

This paper brings details on these new altimeter products and addresses the on-going joint advances in along-track altimeter data processing/assimilation.

Use of GOCE MDT and Error Information in NEMOVAR a Variational Data Assimilation Scheme for NEMO

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The GOCE mission is now producing gravity information of useful accuracy for ocean data assimilation. We test a new GOCE based mean dynamic topography (MDT) along with a new online bias correction scheme, we developed for a 3D VAR assimilation system (NEMOVAR).

NEMOVAR is a multivariate assimilation scheme which assimilates sea level anomaly (SLA), remotely sensed and in-situ sea surface temperature, profile temperature and salinity data, and sea ice concentration data. Assimilating the SLA data requires a MDT to be provided. Currently in the Met Office's operational ocean forecasting system, FOAM, we use the CNES-CLS09 MDT which is a combination of GRACE data, and a synthetic MDT based on dynamic heights and velocities from insitu observations. As GOCE data is accurate to higher resolutions than GRACE this provides the opportunity to use a purely GOCE based MDT but allow a bias correction scheme running online in NEMOVAR to correct the smallest scales of MDT.

The bias correction scheme is designed to focus the bias correction at shorter length scales less than 200km where the MDT errors are known to be larger.

Results are presented from the new Met Office NEMOVAR system running at 1/4 degree global resolution. Several experiments are performed testing different MDTs and bias correction schemes. We compare the bias corrected MDTs to alternative MDT products. The results are assessed by looking at the observation minus background errors. In addition we compare to surface drifters and by examination of the transport estimated by the model along various standard sections.

Altimeter Data Assimilation into Ocean Models: Robustness of the Incremental 4DVAR for Strongly Eddy-active Ocean Circulations

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Data assimilation (DA) encounters increasing interest for various aspects of oceanographic activities with some emphasis in operational oceanography and in the prospects of climate prediction. In practice, most operational oceanography centers use so far sequential DA methodology but variational approach has been widely used in research mode.

In meteorology, the variational techniques are the most favored in practice although some recent approaches consider some type of hybridation (e.g. Ensemble 4DVAR). In practice, most numerical weather forecasting centers use the Incremental declination of the 4DVAR DA (following Courtier et al., 1994). The present work takes place in the context of applying the 4DVAR DA technique to oceanography, especially for strongly non-linear oceanic flows, to make an optimal use of altimeter data of various missions, independently and jointly. One challenge for 4DVAR is to properly cope with strongly non-linear situations, especially assessing the validity of the tangent linear hypothesis. The second question is to optimize the length of the assimilation windows with regard to altimeter satellite orbit periods.

At this stage, we performed various numerical experiments in a eddy-active model configuration that mimic the midlatitude ocean situation. Effects of the model resolution has been investigated from the eddy-permitting to the eddy-resolving cases. Twin experiment framework is chosen and altimeter data is simulated for various satellite configurations (Jason1/2, GFO, Envisat, SARAL)

Overall, the incremental 4DVAR data assimilation in this configuration proves to be more robust than expected for a large range of DA windows. The incremental approach appears to be quite robust even for long DA windows for which the tangent linear hypothesis may have thought to be more problematic. However, our results show the importance of the length of the data assimilation window on the performances, thus assessing some of the results by Luong et al. (1998). We implemented an alternative strategy with iterative sequences of increasing length for the data assimilation windows. It is proven to be more efficient in the prospect of re-analysis that are of particular interest in operational oceanography. This "progressive assimilation" conciliates convergence and longer length of assimilation window, but significantly increases the DA numerical cost.

In addition, we explore the role of the DA window length on the forecast capabilities at mid and longer terms. As we could expect, it is clearly seen that longer DA window are beneficial to long term contrary to short term predictions. We looked at with some details on the performances for various satellites scenarios. The convergence of surface variables is rather insensitive to satellite sampling parameters but this is not the case for oceanic variables at depth. One issue is to relate the space and time altimetric satellite sampling scales to the length of the DA window.

Accounting for Spatial Error Correlations in Altimetric Data Assimilation

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The Kalman filter is a widely spread data assimilation method in oceanography. The standard Kalman filter observational update requires the inversion of the innovation error covariance matrix, what is prohibitive regarding its size. Most implementations of the Ensemble Kalman filter circumvent this difficulty assuming the diagonality of the observation error covariance matrix, that makes the analysis calculation numerically tractable. However, when observation errors are actually correlated spatially, such hypothesis yields too much weight to the observations, and may lead to an inappropriate use of the observations. Spatial altimetric measurements, because they are performed along tracks, are very likely subject to spatial error correlations. In this presentation, we describe a parameterization of the observation error covariance matrix that preserves its diagonal shape, but represents a simple first order autoregressive correlation structure of the observation errors. This parameterization is based upon an augmentation of the observation vector with gradients of observations. Numerical applications to ocean altimetry show the detrimental effects of specifying the matrix diagonal when observations errors are correlated, and how the new parameterization not only removes the detrimental effects of correlations, but also makes use of these correlations to improve the data assimilation products.

Monitoring marine Debris from the March 11, 2011 Tsunami in Japan with the diagnostic Model of surface Currents

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Near-realtime diagnostic model of near-surface ocean currents (SCUD) is developed using the mean dynamic topography and satellite data of altimetry (sea level anomaly) and scatterometry (wind stress), with the coefficients optimized to reproduce concurrent velocities of drifting buoys, drogued at 15m depth. Model experiments, simulating motion of debris from Tohoku area in Japan, are used to assess real-time location of tsunami debris, describe its fate, build the timeline of debris impact on different coast lines and suggest a plan of action, optimizing the use of resources. Model outcome is compared with reports of sightings of various types of debris. Figure. Location of tsunami debris at the moment of the abstract submission, assessed with the SCUD model.

Overview of Ocean Thermal Energy Conversation capabilities, using Mercator GLORYS2v1 Reanalysis

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Oceanographic expertise can help to provide an overview, in order to know where Ocean Thermal Energy Conversion (OTEC) industry could be efficiently raised. OTEC industrial constraints are basically known: vertical temperature gradient, depth of the deep water collecting system, vicinity to distribution area (distance to the coast), type of bathymetry, hydrodynamical constraints (currents, vertical shear, sea state...).

Ocean reanalysis are good tool to describe the ocean thermodynamics in the past. The GLORYS2v1 global ocean reanalysis performed at Mercator Océan aims to provide an accurate description of the global ocean circulation from 1992 to 2009. Satellite altimetry and Argo data play a major contribution in controlling large and medium scale ocean dynamics through assimilation. The water mass circulation provided by the NEMO model, global ocean 1/4° configuration, is corrected by these observations, from the surface to the deep ocean.

This integrated global ocean description is used to define the potential usefulness of OTEC worldwide. The ocean thermal content at interannual, seasonal and intraseasonal time scale is assessed in every basin to map the OTEC usefulness from surface to 2000-m-depth. Most of the potential OTEC areas are located in the tropical band. But considering ocean heat transport and heat content variability, some particular zones of tropical oceans can be excluded, using OTEC criteria. Thanks to this global assessment potential areas can be identified at global scale. Further impact studies, using regional approaches both based on modelling and observations should be then carried on to better evaluate the interest of specific areas, in particular taking into account coastal dynamics near tropical islands and continental shelves.

WMO Requirements for Satellite Radar Altimetry

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The World Meteorological Organization (WMO) places high importance on exploiting the opportunities provided by 20 years of satellite altimeter operations for the benefit of science and society. Through a number of Programmes and co-sponsored Programmes (such as Global Climate Observing System - GCOS) supported by its 183 Member states and jointly with the Intergovernmental Oceanographic Commission, requirements for altimeter datasets have been identified or are under development. These will be discussed in this paper for the areas of (i) oceanography and marine meteorology, (ii) coastal inundation forecasting and warning, (iii) hydrology, through monitoring of lakes and rivers, (iv) the cryosphere, (v) climate monitoring, (vi) climate modeling and forecasting. In these six WMO-related applications, the combination of altimetry with other satellite-based techniques, in-situ data (e.g., river gauges, tide gauges), and modelling capacity (e.g., river basin runoff model; storm surge model) has been identified as providing additional information and confidence in the results. The 2011 update to the GCOS requirements for sea level and lake level altimeter products will also be described, along with the importance of altimetry in WMO planning of global observing systems until 2025. The paper stresses that continuing research is required to fully explore the impact of altimeter data on these priority areas for WMO (e.g., related to assimilation in ocean modeling frameworks). At the same time, in many respects, altimetry products and processing frameworks have reached a degree of maturity where their use in (quasi)operational, sustained applications and services should be fostered, for example in the context of the Global Framework for Climate Services.

Poster Session: Oceanography – Large Scale

Sea Surface Height Variability in the Gulf of Thailand and South China Sea using altimetry Data : A Preliminary Study

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Monthly mean TOPEX/Poseidon, ERS-2, ENVISAT, Jason-1 and Jason-2 crossover data in the Gulf of Thailand (GOT) and South China Sea (SCS) are used to investigate the spatial and temporal variability of sea surface height anomaly (SSHA). Distribution of SSHA shows two modes: (1) Low water level remains along the axis with heights on both sides (coasts of Asian continent, Borneo and GOT) when northeast monsoon prevails (November to January) (2) High water level remains along the axis with lows on both sides when southwest monsoon prevails (May to August). This regular or normal mode is affected by ENSO events. Analysis of satellite altimetry data also yields an average sea level height rise of 4-5 mm/yr in the GOT and a higher rate of rise in the SCS.

Observations of Brazil Current baroclinic transport near 22ºS: Variability from the AX97 XBT Transect and Satellite Altimetry

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Recent progress in understanding the Brazil Current (BC) mean flow and associated features has been achieved, however, several aspects of BC low-latitude variability remain unexplained mostly due to the lack of observations. For example, south of 18ºS, the BC poleward flow is normally thought to be largely composed of eddies, which leads to an ill-defined mean current with strong temporal and spatial fluctuations. This large variability leads to uncertainties in the baroclinic transports estimates from isolated and sporadic hydrographic transects. In order to increase the number of observations of the BC in this area, Brazilian institutions and NOAA have partnered to implement a long-term high-density XBT (eXpendable-BathyThermograph) transect in the southwestern Atlantic. This project has been named MOVAR (*Monitoring the upper ocean transport variability in the western South Atlantic*) and the XBT transect has been designated as AX97. The MOVAR project collects XBT data from Brazilian Navy supply ships that sail from Rio de Janeiro to Trindade Island (30ºW, 20ºS) with a frequency of up to 5 times per year. A total of the twenty-nine complete realizations of the AX97 transect have been carried out between August 2004 to December 2011. One of the main objectives of this transect is to build a long-term time series of the BC baroclinic transports (and associated features) in order to improve understanding of the this infrequently-sampled area of the South Atlantic Ocean. The mean AX97 baroclinic velocity field as derived from XBT observations indicates the presence of the main BC, clearly confined to the west of 39ºW with its mean core position located at about 200 km from the coast at local water depth of about 2200 m. The maximum mean baroclinic velocity exhibits values of up to 0.2 m s^{-1} in the core of the BC. The standard deviation of the BC is comparable magnitude to the mean (0.2 m s^{-1}) in the BC core, highlighting the importance of the spatial and temporal variability in the BC regime at 20ºS. In addition, relatively large coherent mesoscale structures along the entire AX97 transect are evident in the mean and in the standard deviation sections. To gain further insight on the large-scale nature of the variability observed along AX97, we use the regional surface geostrophic circulation fields derived from the Maps of Absolute Dynamical Topography (MADT) dataset produced by AVISO combining all available satellite altimetry data. The use of satellite altimetry data reveals that the fluctuations of the axis of the BC and even the absence of the main jet from the AX97 line are the main causes of the observed variability of the baroclinic transports. Furthermore, the MADT fields unveiled that the observed variability is associated with large scale fluctuations of the northern high-cell of the South Atlantic subtropical gyre.

Investigation of the Interannual Variability of the Tropical Atlantic Ocean from Satellite Data

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The low frequency (interannual) variability of the tropical Atlantic Ocean is analyzed with series of altimetric dynamic topography data, sea surface temperatures, and wind stress between Ocotobre 1992 and January 2011 using Empirical Orthogonal Functions and Singular Value Decompositions. Three regions of maximum variability are evidenced: a northern one, between 10 and 20ºN, where altimetry, sea surface temperature and wind stress are strongly connected through thermosteric and Ekman pumping effects in particular in 2010 but also in 1998 and in 2005; A southern region, along 20ºS, where dynamic topography decreases in particular in 1997 and in 2010 in agreement with surface cooling and southern tradewinds intensification; An equatorial region whose variability appears either as an Est-West slope of the topography and temperature all along the equator (2005 and 2010) or as a (cold) tongue in the Gulf of Guinea (1997 and 2002). Both local wind (meridional component) and western remote (zonal component) effects can be involved in this oceanic triggering. First results of the teleconnections between this tropical Atlantic interannual variability and the tropical Pacific El Niño–Southern Oscillation indicate a possible connection of the tropical Atlantic between 10-20ºN with a 19 weeks delay, and in the Gulf of Guinea with a 70-80 weeks one.

Interannual Variability of Tropical Warm Pools in Remote Sensing Based and ECCO-assimilated Oceanographic Data Sets

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Interannual variability of the west Pacific Warm Pool (WPWP) and west Atlantic Warm Pool (WAWP) sea surface temperatures (SSTs) and their association with ocean surface variables are investigated with remote sensing based 27-yr (1982-2008) Optimal Interpolation SST; 15-yr (1993-2008) sea-surface height (SSH) from TOPEX/Poseidon, Jason-1, and ERS 1/2; 9-yr (1999-2008) surface wind stress (SWS) from QuikScat; and 15-yr (1992-2007) surface current (SC) from Ocean Surface Current Analyses-Real time (OSCAR) data sets. Data products from the 12-yr (1992-2004) Estimating the Circulation and Climate of the Ocean (ECCO) oceanic reanalysis system were also used in this study.

Two EOFs well represented the WPWP SST interannual variations. These anomalous SST patterns evolved largely in situ in the WPWP region, and also co-varied with SST anomalies in the eastern and central Pacific and the Indian Ocean. SSH variability was physically consistent with SST variability in some years. A thermally-direct atmospheric response to the WPWP SST anomalies was implied by anomalous SWS convergence over warmer than average SSTs. SC anomalies were associated with SWS anomalies near the WPWP. SST analyses also show that more than half of the interannual WPWP SST variance is not explained by simultaneous ENSO variability, suggesting that intrinsic ocean-atmosphere interactions in the WPWP region may also be important, especially at the sub-decadal to decadal timescale. An estimation of the terms in the SST tendency equation, using ECCO data, showed that the tendency was dominated by net surface heat flux, especially latent heat flux, with a negligible role of advection terms in determining SST tendency. In the mixed-layer temperature tendency equation, however, anomalous zonal and meridional temperature advection by time-average currents played dominant roles and thus showed the important role of ocean dynamics. In the tendency equation for temperature in the 50 m layer below the mixed layer also, the zonal advection process determined the temperature tendency. Results for the WAWP were similar to the WPWP analysis results.

These results show that the quality of multi-decades long, independently-estimated, remote sensing based ocean surface variables is high enough that a coherent, physical picture of interannual variability of tropical warm pools can emerge from analyses of these data sets; altimeter-based SSH estimates play a crucial role in understanding warm pool variability. These and the ECCO results also imply that ocean dynamical processes, in addition to ocean-atmosphere interactions via surface heat flux, are also involved in interannual variability of tropical warm pools. The time series of remote sensing based and ECCO-assimilated data sets should be continued so that decadal and longer timescale variability can also be studied with these data sets.

Large-scale Interannual Variability of Sea Level and Water Mass Properties in the Southeast Pacific

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The southeast Pacific sector of the Southern Ocean plays an important role in regulating the climate of Antarctica. This is the region where the Antarctic Circumpolar Current (ACC) reaches its southernmost latitude and brings heat towards the western side of the Antarctic Peninsula, and where the biggest source of the Antarctic Intermediate Water (AAIW) formation is located. Nearly 20 years of high accuracy satellite altimetry measurements have revealed a large-scale pattern of the interannual variability of sea surface height (SSH) in the region. Three phase changes occurred during the observational period: in 1998, 2003, and 2008. The positive (negative) phase is associated with higher (lower) than average sea level west of the South America and lower (higher) than average sea level over the ACC and south of it. We have shown that the observed variability of SSH is related to wind forcing over the region, and to Pacific Decadal Oscillation suggesting the importance of large-scale teleconnections. The wind strengthens/weakens the convergence/divergence zones that is reflected in the SSH variability. The flow of the ACC is known to be concentrated in jets that are associated with frontal regions. We use altimetric measurements of SSH to detect the ACC fronts and to establish their relation, in terms of location and strength, to the observed interannual fluctuations of SSH and wind stress. We also use the Southern Ocean optimized solution from the ECCO2/ECCO3 (Estimating Circulation and Climate of the Ocean, Phases 2 and 3) ocean data synthesis and available hydrography data (mainly based on ARGO measurements) to investigate the associated interannual changes in water mass properties. Particular attention is paid to the variability of the AAIW. Preliminary statistical analysis of the ECCO2 model output shows that the vertical distribution of salinity is strongly coupled to sea level and wind stress; convergence/divergence of Ekman transport west of the Drake Passage corresponds to an decrease/increase of salinity in the surface layer and in the core of the AAIW.

Seasonal Coupling in the Gulf Stream Region between the Atmosphere and the Ocean

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Seasonal coupling in the Gulf Stream region between the atmosphere and ocean is investigated using models and observations. Heat budget analysis in a regional diagnostic model constrained by SSH (sea surface height) observations shows that on interannual time scales, the heat content in the upper ocean leads the flux of heat from the ocean to the atmosphere by approximately three months, with a warmer ocean leading to oceanic heat loss. These results are consistent with that found in an eddying, data-constrained simulation provided by the ECCO2 (Estimating the Circulation and Climate of the Oceans, Phase II) project. To investigate the seasonal dependence of the coupling, we calculated the lag correlation for multi-year time-series of upper ocean heat content and surface heat flux for each month of the year for the model, and between sea surface height (SSH) from AVISO as a proxy for upper ocean heat content and surface turbulent heat flux from the OAFLUX project. For the period between 1993 and 2011 in a region encompassing the separated Gulf Stream between 33N and 43N and 75W and 57W, significant correlations were found with the ocean leading the atmosphere by a season during two different times of the year. Summer ocean heat content leads late fall surface flux south of the Gulf Stream where the maximum winter mixed-layer depth is deepest. During late fall the flux of heat is out of the ocean as the mixed layer nears its maximum depth; the atmosphere then has access to the heat stored in the deep.layer. Later in the winter, the deep heat content looses its memory of the previous year as it is more directly effected by the atmosphere. North of the Gulf Stream spring ocean heat content leads surface flux in early summer. Here, the turbulent heat flux is into the ocean in the early summer and the mixed-layer is shallow with warm atmosphere overlying the cold ocean. During this time of the year the atmospheric boundary layer is shallow and stable and the surface winds are relatively quiet compared to other times of the year. Because of the lack of influence of tropospheric processes in the boundary layer, the atmosphere at the surface is influenced by ocean. These results suggest that during the summer, the influence of the ocean will likely not be felt outside of the boundary layer, while in the late fall, because the boundary layer is unstable and communicates freely with the troposphere, the ocean may have an impact on the atmosphere beyond the Gulf Stream region. Lagged auto-correlations show that heat content anomalies persist for several months, while surface flux anomalies do not. The results show that ocean heat content may have predictive skill for the atmospheric state in late fall and early summer.

A 20-Year Satellite Climatology of Ocean Circulation in the Northern Indian Ocean

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Over the past twenty years, progress has been made in defining and understanding the seasonal circulation along the east and west coasts of India, where the major features are: (i) the East India Coastal Current (EICC), (ii) the larger-scale Bay of Bengal gyral circulation; and (iii) the West India Coastal Current (WICC). This has been accomplished through traditional oceanographic hydrographic cruises (Babu et al., 1991; Murty et al., 1992; Shetye et al., 1993; 1996), analytic and numerical modeling studies (Shankar et al., 1996; McCreary et al., 1996) and (more recently) analysis of satellite altimeter data (Somayajulu et al., (2003); Durand et al., 2009; Vialard et al., 2009; Shenoi, 2010; Nienhaus and Subramanhyam, 2012). Most of this work has focused on the EICC and the Bay of Bengal, where the coastal currents flow against the strong monsoon wind forcing. This apparent anomaly has been explained as the consequence of coastal Kelvin waves that originate along the eastern margin of the Bay of Bengal or of even more distant Equatorial Kelvin waves. The role of Rossby waves in bringing signals from the east to the southern tip of India has also been examined using satellite data. The sea level signal carried by the Rossby waves may reinvigorate the coastal Kelvin waves as they continue their path along India's western coast. In our presentation, we will build on these previous studies to examine the annual and interannual variability in the circulation of both the EICC and WICC, as well as their connections to the larger-scale Northern Indian Ocean. To do this, we will primarily use altimeter data (both gridded AVISO and alongtrack retrievals closer to the coast). These will be combined with a longer record of infra-red satellite SST and shorter records of satellite-derived surface chlorophyll pigment concentrations (SeaWiFS) and surface wind stress (QuikSCAT). Statistical methods (EOFs and Principle Estimator Patterns) will be used to explore the connections between regions. Results of idealized and realistic numerical modeling studies of the circulation will be compared to the results of the satellite analyses.

Detection of the MJO Signal from Altimetry in the Indian Ocean

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The Madden-Julian Oscillation (MJO) is an envelope of organized convection that propagates from the Indian Ocean to the Pacific Ocean and constitutes the dominant form of intraseasonal precipitation and atmospheric circulation variability in the tropics. The MJO influences a variety of tropical weather and climate phenomena, including tropical cyclones (affecting hurricanes in the Gulf of Mexico), the onset

and intraseasonal fluctuations of the monsoons and rainfall over Asia, Australia, Africa, and the Americas, and the onset of El Niño events. Despite its importance and concerted efforts over several decades, the MJO has not yet been adequately explained, and global atmospheric circulation models have difficulty simulating and predicting it.

In this work the role of air-sea interaction on MJO propagations across the tropical Indian Ocean is analyzed using 20 years of satellite altimetric measurements of Sea Surface Height (SSH) and Outgoing Longwave Radiation (OLR). Wavelet analysis of OLR and SSH revealed the interaction of oceanic and atmospheric properties. MJO-related activity is observed in both parameters in the eastern equatorial Indian Ocean indicating a unique interaction in this region. In the eastern Indian Ocean atmospheric conditions appear to aid in the creation of equatorial Rossby waves while in the central and western Indian Ocean, different phases of oceanic Rossby wave propagations seem to have a strong influence on atmospheric conditions associated with the MJO. The downwelling phase of equatorial Rossby waves in SSH corresponds to a strengthening of OLR anomalies in extent and magnitude across the equatorial Indian Ocean while the upwelling phase appears to weaken atmospheric MJO activity. From this study it is evident that different phases of Rossby wave propagation either enhance or suppress MJO activity in the Indian Ocean. Using SSH measurements to understand the MJO serve as an important resource to understand the sea surface conditions that may trigger an MJO propagation.

Patterns of Indo-Pacific Inter-basin Sea Level Change During Recent Decades

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Tide gauge and satellite observations from 1993-2010 show large sea level rising rates of >9 mm/yr in the tropical western Pacific, weak falling trends in the eastern tropical Pacific together with the US west coast and rising trends in extratropical basin interior centered near 40°N and 40°S. Over the Indian Ocean, apparent sea level rise occurs in the south tropical-subtropical basin. Existing studies have examined the sea level changes separately in different regions, but did not view the sea level change with a basin-wide perspective. Do the sea level changes in different regions vary independently, or they belong to a basin-wide coherent sea level change pattern? What is the cause for the inter-basin decadal coherent sea level change in the coupled ocean-atmosphere system of the Indo-Pacific basin? Answering these questions is imperative and could benefit the society. Here, we use the approach of combined observational analysis and modeling experiments to investigate the causes for the Indo-Pacific sea level pattern from 1993-2010. The analysis also is extended to the 1950s and 1870 using available observations, reconstructed data and reanalysis products, in order to understand whether the changes during 1993-2010 are part of the decadal-multidecadal variability or longer-term trend. Our analysis shows that the spatial pattern of sea level trend from 1993-2010 results primarily from a basin-wide coherent change that is driven by wind and convection associated with the Indo-Pacific interbasin decadal variability (IDV) in the coupled Indo-Pacific climate system, whose signatures over the Pacific Ocean represent the Interdecadal Pacific Oscillation (IPO; Power et al. 1999), and we refer it to as IPV (variability). Experiments using three independent Atmospheric General Circulation Models (AGCMs) suggest that the changing wind and convection that drive the sea level change from 1993-2010 are primarily forced by the tropical (20S-20N) Indo-Pacific SST: Warm SSTs in the Indo-Pacific warm pool and cold SSTs in the central-eastern Pacific - which is associated with IPV positive-to-negative phase transition - act in concert to force the surface wind and convection patterns. Of particular interest is the unusual SST pattern, with a negative IPV phase (La Nina like) in the Pacific corresponding to a basin-wide warming in the Indian Ocean. This pattern is in contrast to the lowpassed 8-yr SST EOF1 for 1870-1977, which shows that a positive IPV phase (El Nino like) corresponds to a tropical Indian Ocean warming, an effect that resembles the El Nino-induced warming on interannual timescales. The change occurred after 1977 (since 1980). This new Indo-Pacific IDV pattern of SST may suggest that instead of being a slave of the Pacific IPV, the Indian Ocean may play a more active role in affecting the Indo-Pacific "decadal" variability in a warming climate. The SST trend pattern from the ensemble mean of NCAR's CCSM4 supports this result.

The Azores and St. Helena Currents from Two Decades of Satellite Altimetry: Inspecting their Congeneracy and Roles in the Subtropical Atlantic

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Two decades of satellite altimetry with synergistic use of other remote sensing variables (e.g., Sea Surface Temperature), in situ and GOCE (Gravity field and steady-state Ocean Circulation Explorer) data, are used to assess the congeneracy of Azores (AzC) and St. Helena currents (StHC) and their associated fronts, aiming to achieve a finer description of the ocean circulation variability over the North and South Subtropical Atlantic basins (meso and large scales). Earlier studies on both current systems, using mainly hydrological measurements, suggest a similar forcing source independent of any geographical peculiarity, the two current systems showing similar characteristics regarding intensity, depth penetration, volume transport, and zonal flow. Also, both currents have associated subsurface adjacent countercurrent flows, and their main cores are found at similar latitudes (34ºN and 34ºS for the AzC and StHC, respectively).

Multi-mission satellite altimetry data records are at present long enough to appropriately study the annual signal in the ocean surface circulation and to infer the long-term variability on multi-annual periods. Satellite altimetry, in combination with a mean dynamic topography (MDT) model computed from in situ data, was previously used to derive a time series of absolute dynamic topography (ADT), which allowed the study of the AzC variability over the 1995-2006 period, namely the existence of inter-annual variability in its axis position. In addition to extending the previously used altimetric data set for the AzC, a similar study for the StHC is a requisite to the assessment of possible resemblances between both currents in what concerns their inter-annual variability. In order to accomplish this purpose, the use of in situ and/or GOCE data for the South Atlantic are exploited to generate an altimetry-independent MDT with a spatial resolution that matches that of the altimetry-derived oceanographic fields (sea level anomaly, ADT, eddy kinetic energy, etc.) used in this study (0.25ºx0.25º). Furthermore, the surface thermal signatures of the currents/fronts are compared to the corresponding ADT-derived signatures.

Results are expected to improve the knowledge of the South Atlantic variability, the Atlantic inter-hemispheric connections and the correlation of long-period variability of the above referred oceanographic fields with the known phenomena of coupled atmosphere-ocean variability that affect the Atlantic, which are expected to occur on inter-annual to decadal time scales.

Dynamics of SST Anomalies in the Southern Ocean Diagnosed from a 2D Mixed-layer Model with Advection Prescribed from Altimetry

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The Southern Ocean is a major ventilation window where mode and intermediate waters form at the northern edge of the ACC. Properties of newly formed waters are set in the ocean mixed layer, hence the importance of documenting and understanding its year to year changes.

Here we analyze the processes responsible for the generation and evolution of sea-surface temperature (SST) anomalies observed in the Southern Ocean during a decade based on a 2D diagnostic mixed-layer model in which geostrophic advection is prescribed from altimetry.

Anomalous air-sea heat flux is the dominant term of the heat budget over most of the domain, while anomalous Ekman heat fluxes account for 20-40% of the variance in the latitude band 40º-60ºS. In the ACC pathway, lateral fluxes of heat associated with anomalous geostrophic currents are a major contributor, dominating downstream of several topographic features, reflecting the influence of eddies and frontal migrations.

A significant fraction of the variability of large-scale SST anomalies is correlated with either ENSO or the SAM, each mode contributing roughly equally. The relation between the heat budget terms and these climate modes is investigated, showing in particular that anomalous Ekman and air-sea heat fluxes have a co-operating effect (with regional exceptions), hence the large SST response associated with each mode. It is further shown that ENSO- or SAM-locked anomalous geostrophic currents generate substantial heat fluxes in all three basins with magnitude comparable with that of atmospheric forcings for ENSO, and smaller for the SAM except for limited areas. ENSO-locked forcings generate SST anomalies along the ACC pathway, and advection by mean flows is found to be a non-negligible contribution to the heat budget, exhibiting a wavenumber two zonal structure, characteristic of the Antarctic Circumpolar Wave. By contrast SAM-related forcings are predominantly zonally uniform along the ACC, hence smaller zonal SST gradients and a lesser role of mean advection, except in the South-West Atlantic.

While modeled SST anomalies are significantly correlated with observations over most of the Southern Ocean, the analysis of the data-model discrepancies suggests that vertical ocean physics may play a significant role in the nonseasonal heat budget, especially in some key regions for mode water formation.

Variability of the ACC Transport Across the Kerguelen Plateau

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The Kerguelen Plateau is a major topographic obstacle barring the way of the eastward flowing Antarctic Circumpolar Current (ACC). Whilst approximately two thirds of the ACC transport is diverted to the North, most of the remaining flow engulfs in the Fawn Trough, the only deep passage across the Plateau. As part of the TRACK (TRansport ACross the Kerguelen plateau) project, three mooring lines of current meters were deployed in the Fawn Trough for one year in February 2009, underneath ground-track 94 of the Jason-2 satellite altimeter. Full depth CTD-LADCP casts carried out during the deployment cruise were previously analyzed to provide a comprehensive description of the regional circulation (Park et al., GRL, 2009), featuring in particular a transport of about 40 Sv across the Fawn Trough.

Here we focus on the transport variability across the Fawn Trough determined from current meter data.

We examine to what extent the transport can be directly monitored from along-track satellite altimeter data, which would enable to study the variability of the current from a now 20-year long archive.

Finally we discuss processes forcing the variability of the current.

Definition of Special Position of the Southern Ocean and Antarctic Circumpolar Current Boundaries Based on Remote Sensing Data

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The feasibility and effectiveness of satellite altimetry and radiometry using for studying the thermodynamic structure and dynamics of the Southern Ocean were demonstrated. Analysis of the temporal variability of sea level anomalies (SLA), calculated from satellite altimetry data allowed to specify the spatial position of the Antarctic Circumpolar Current (ACC) boundaries and the analysis of sea surface temperature (SST) the northern boundary of the Southern Ocean was specified. Detection of ACC boundaries as isoline 112 cm and 30 cm of mean dynamic topography (north and south, respectively) is consistent with eddy activity and meandering regime of the Antarctic Circumpolar Current.

The spatial position of isoline value 0,88 °C of SST dispersion can be regarded as the southern boundary of the Subarctic divergence zone, and the spatial position of the isoline 1,64 °C - the southern boundary of the Subtropical convergence zne.

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Contribution of Satellite Altimetry to Investigate the Variability of the MOC in the South Atlantic

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This work presents results that use blended satellite altimetry observations together with XBT, Argo profiling float, and climatological data to investigate the year-to-year variability of the meridional overturning circulation (MOC) and meridional heat transport (MHT) along 35°S since 1993. The barotropic and baroclinic components are extracted from the altimetric and hydrographic records. A validation of the barotropic estimates is done using a short record of three pressure equipped inverted echo-sounders deployed in the western South Atlantic along 35°S in 2009-2010. The baroclinic component is validated using the XBT derived MHT and MOC estimates. Results from the altimetry-based methodology during 1993-2010 indicate that the mean MHT ranges between 0.6 and 0.8PW. Large interannual variability is observed with amplitudes of up to 1PW, which is comparable to similar values derived from XBT measurements. Changes in MOC and MHT are analyzed in terms of variations of the wind field and in the subtropical gyre, which has exhibited a warming trend during the last 20 years. Results obtained from this study are used to assess the value of satellite altimetry observations for MOC studies in the South Atlantic Ocean, in particular to extend the time series of the in situ observational record and to obtain estimates where in situ observations are not available.

An Oceanic Heat Budget for Interannual Variability in the Northeast Pacific Ocean estimated from a One-dimensional Model and Sat

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Understanding processes involved in decadal and regional variation in heat content is important to isolating long-term trends associated with global climate change. For example, the Pacific Decadal Oscillation (PDO) is a leading cause of upper ocean heat content, as evidenced by changes in sea surface temperature (SST) and sea surface height (SSH). We combine a numerical model of the upper water column with satellite altimetry measurements to quantify terms in the heat budget leading to observed changes in SSH and SST over multiyear time scales in the northeast Pacific Ocean. A horizontal grid of one-dimensional upper-ocean models forced by atmospheric fluxes reproduces the large-scale pattern and amplitude of SST variability, except in the far eastern Pacific, and, to a lesser extent, SSH variability in the central tropical Pacific. However, most of the changes in SSH are related to adiabatic process (e.g. Ekman pumping), which are not represented in the model. Supplementing the modeled wind-driven currents with geostrophic currents calculated from SSH gradients measured by altimetry allows estimation of the sizes of the terms in the heat budget. The interannual heat budget in the upper 50 meters is primarily a balance between heat storage, surface heat flux, and the advection of the time-mean temperature gradient by long-term variations in the velocity field. The addition of Argo data in recent years constrains the modeled density structure below the mixed layer, improving estimates of subsurface vertical heat flux.

Atlantic Meridional Overturning Circulation Monitoring Using Multi-mission Satellite Radar Altimetry and Other Observations

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Proxy records for the past climate suggest that the Atlantic Meridional Overturning Circulation (AMOC) may have completely halted or partially weakened as a result of the freshwater flooding from the iceberg rafting and meltwater outburst in the North Atlantic. The AMOC, including the Gulf Stream, transports mass, heat and freshwater from the mid-depth and upper layers from the south into the north Atlantic and the Arctic ocean, and returning cold, dense water southward at depth. Observations and climate model simulations indicate that the AMOC may weaken as a result of anthropogenic climate forcing, which in turn might lead to significant cooling over the North Atlantic and its adjacent regions. While the AMOC signals are with interglacial periods or need at least thousands of years to reveal its evolution, available data are from ice and sediment records. During the recent decade or longer, the availability of various satellites and in situ data monitors different components of the ocean circulation and its transport more accurately and with much finer temporal and spatial samplings, and provides potentially insights into the evolution of the AMOC. Here we present the use of contemporary multi-mission radar altimetry inferred sea level and geostrophic surface and subsurface current velocities when combined with hydrographic data, GRACE observed ocean bottom pressure and Alaskan glacier and Greenland ice sheet melt water mass fluxes, sea surface temperature GHRSST data, satellite scatterometry wind, and hydrographic data sets (tide gauges, MBT/XBT/Argo steric sea level and Argo subsurface current velocities down to 2000 m), towards building an observational system to monitor the present-day evolution of the AMOC, and a potential study of possible fingerprinting to link sediment core proxies to modern observations, for example, to study the strength of the Labrador Sea Water formation.

Drake Passage: Circulation, Modes of variability, heat Fluxes and volume Transport revisited using new in situ time Series and satellite Altimetry.

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The Antarctic Circumpolar Current is the only current to circumnavigate the globe and the largest wind-driven current in the world. It encircles Antarctica and plays an important role in global climate by connecting all the major oceans, mixing water and properties. Located between South America and Antarctic continents, Drake Passage (DP) is the narrowest stretch of water separating Antarctica from other continents (800 km), and as such, it exerts a strong constraint on both path and strength of the Antarctic Circumpolar Current.

Time series of velocities were obtained at nine mooring sites across the Drake Passage (DP) during 36 months (February 2006-April 2009). They documented the mean flow, variability and vertical structure of the Antarctic Circumpolar Current (ACC) across Drake Passage, as well as the predominant time scales during this period. A permanent deep cyclonic circulation was observed in both the Yaghan and Ona Basins. Mean near surface velocities in the center of the Yaghan Basin were westward and call for a revision of the existing mean dynamic topographies. The moorings were located under the Jason satellite ground-track #104, allowing precise comparisons with various altimetry products. The in situ data allowed us to assess the quality of the altimetric data and in return the altimetric data helped our understanding of the large-scale oceanic structures in which the point measurements were embedded. Altimetric data also allowed us to situate the 3-year-long currentmeter time series within the 18 years of satellite measurements. Altimetrically derived surface geostrophic velocities were used to further investigate modes of variation of the flow in the northern part of the Yaghan Basin, over the West Scotia Ridge, and, in the Ona Basin to the shelter from the eastward flowing Antarctic Circumpolar Current provided by the highest part of the Shackleton Ridge.

Mean heat fluxes and eddy heat fluxes were computed from the in situ data. Topography made possible large meridional mean heat fluxes in the center of the Yaghan and Ona Basins. Meridional eddy heat fluxes were large over the West Scotia Ridge. Undergoing volume transport computations will be presented and discussed. An operational model is being used to rationalize mean and eddy heat flux estimates and to evaluate error bars in the volume transport estimations.

Investigation of Mediterranean Mean Sea Level Variability from Satellite Altimetry

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The sea level change is a crucial indicator of our climate. The spatial sampling offered by satellite altimetry and its continuity during the last years are major assets to provide an improved vision of the Mediterranean mean sea level.

In this study, Singular Spectrum Analysis (SSA) is applied to investigate the seasonal and interannual variability of Mediterranean mean sea level. Considering the averaged Sea Level Anomalies (SLAs) time series that extend back to 1993, the SSA technique shows that the Mediterranean mean sea level is dominated by several harmonics.

The first dominant components have periods of about 51.99 weeks (annual signal), 26.00 weeks (semi-annual signal) and 31.63 weeks (~7 months). The annual signal is particularly strong in the Mediterranean Sea and represents 72.38% of the initial signal. Our Mediterranean sea level trend is estimated to 1.72 mm yr-1 for the period from 1993 to 2010.

On the Surface Circulation of the Levantine Sub-basin Derived from Lagrangian Drifters and Satellite Altimetry Data

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The surface currents of the Levantine sub-basin (Mediterranean Sea) are described using 19 years (1992-2011) of drifter data and satellite-derived sea level anomalies. The combination of drifter and satellite data allowed to estimate maps of surface geostrophic circulation and to obtain more accurate pseudo-Eulerian velocity statistics for different time periods. Seasonal and interannual variability of surface currents are investigated with particular focus on the main sub-basin eddies of the eastern Levantine. The mean velocity field depicts the typical patterns of the along-slope and offshore currents and outlines the sub-regions where eddies are generated recurrently (west Egyptian coast, Ierapetra, Mersa-Matruh, south-west of Cyprus, Israel-Lebanon coast, Latakia) or persist steadily (Rhodes Gyre). Highly variable and energetic currents are observed between the Ierapetra and Mersa-Matruh regions, as the result of the interaction of the Mid-Mediterranean Jet meandering in between, and interacting with, the eddies generated by the instability of the coastal current. Seasonal pseudo-Eulerian maps shows the current field stronger in summer and weaker in winter, mainly in the western Levantine and in the Cyprus-Syria Passage. The Shikmona Eddy displays a periodic nature with higher intensities during the cold months and an enhanced activity in the period 1998-2006. The Cyprus Eddy has a less periodic nature, characterised by events of high activity and periods in which it dominates as a single enlarged eddy in the southeast Levantine, eventually including the Shikmona Eddy. The Latakia Eddy is mainly cyclonic with higher intensities in summer and fall; occasional weekly or monthly inversions of circulation from cyclonic to anticyclonic are triggered by the interaction between the MMJ and the northward coastal meandering current.

Decadal Variability of Net Water Flux at the Mediterranean Sea Gibraltar Strait

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Long-term variability of the net water flux into the Mediterranean Sea at the Gibraltar Strait over the period 1960-2011 is explored based on an approach combining multiple observational datasets and results from a regional climate model simulation.

The approach includes deriving Gibraltar water fluxes from the application of the Mediterranean Sea mass conservation equation using observationally based estimates of mass variation from GRACE, sea level and its steric component from satellite altimetry, sea level reconstruction and in-situ data, evaporation, precipitation and simulated river discharge and Bosphorus Strait water fluxes. This derivation is compared with results from a simulation using the PROTHEUS regional ocean-atmosphere coupled model considering both individual water cycle terms and overall Gibraltar water flux.

Results from both methodologies point to an increase in net water flux at Gibraltar over the period 1970-2009 (0.8 +/- 0.2 mm/mo per year based on the observational approach). Simulated Gibraltar net water flux shows decadal variability during 1960-2009 including a net Gibraltar water flux decrease during 1960-1970 before the 1970-2009 increase. Decadal variations in net evaporation at the sea-surface, such as the increase during 1970-2009, appear to drive the changes in the net inflow at Gibraltar, while river runoff and net inflow at the Bosphorus Strait have a modulating effect. Mediterranean Sea mass changes are seen to be relatively small compared to water mass fluxes at the sea surface and do not show a long-term trend over 1970-2009. The Atlantic Multi-decadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) are seen to influence net water flux at Gibraltar indirectly via the influence they bear on regional evaporation, precipitation and runoff.

The extension of the study to the interval 1960-2011 includes mass variation derived from improved GRACE gravity field solutions.

Interannual Variability of the Black Sea Level Basing on the Radar Altimetry

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The Black Sea level varies in response to global and regional climate changes. In accordance with in situ measurements, it increased by 20 cm in the last 100 years. Satellite altimetry enables tracing of seasonal and interannual variability of sea level both of the sea as a whole and of individual regions from September 1992 to the present time. Information and software of the Integrated Satellite Altimetry Data Base (ISADB) developed in the Geophysical Center of Russian Academy of Sciences were used for the Black Sea altimetry data processing and analysis. The analysis was based on altimeter data of the TOPEX/Poseidon, Jason-1 and Jason-2 satellites for 1993-2009 time period. For all satellite altimetry data all necessary corrections were used without tidal and inverse barometer corrections. An increase of the Black Sea level in 1993-1999, 2003-2004 and 2008-2009 was established, with its noticeable decrease after the high of 2004. Calculations have shown that during the period from January 1993 to September 2008 sea level in the sea as a whole increased with velocity of 1.34±0.11 cm/year; in the western and eastern regions it increased with velocity of 1.42±0.16 and 1.28±0.12 cm/year, respectively. For comparison, from the middle 1920s to about 1985 sea level increased with 1.83±0.7 mm/year. Thus, velocity of sea level rise in the last 16 years was about seven times greater than in the preceding half a century. The general sea level rise, interannual and seasonal variability in 1993-2002 correlated well with a variability of the Danube River discharge. Since 2003, surprisingly, there is no more correlation between the Black Sea level and the Danube River discharge. The interannual variability of the total Danube runoff at 54 mile transit during the period 1982-2009 was analyzed and its continuing growth at the present time was set. Estimated runoff trends appeared to be +1.1 km3/year and +0.8 km3/year in 1982-2009 and 1993-2009, respectively. The trends obtained for these relatively short time intervals (27 and 16 years) are several times higher than the known average for more than a hundred period 1860-1987 (+0.126 km3/year). In addition, weekly Pathfinder data (1982-2009) with spatial resolution of 4 km were used to investigate interannual and seasonal variability of sea surface temperature (SST) in the Black Sea (the sea as a whole and its three regions: near-Bosporus, northeastern, and near-Kerch regions). Further warming of the Black Sea was found, with trend of mean annual temperature of about 0.06º ñ/year, 2007-2009 being the years with the highest mean annual temperature in the period under consideration. The correlation analysis for the Black Sea level variability was completed by the analysis of atmosphere pressure and precipitation variability over the Black Sea.

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Estimation of the Geophysical Parameters and the Orbital Error Effect on the Altimetric Measurements for Sea Surface Height Determination

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The emergence of satellite altimetry has allowed us to determine the ocean surface with a great precision; it also allows a large contribution for most applications and oceanographic activities. The geometric principle of space altimetry is to measure the range between the satellite and the sea surface.

The objective of this paper is to estimate the geophysical parameters (sea state bias, ocean tide and the orbital error) affecting the altimetric measurements for Jason-1 satellite, using the analytical and empirical models. The orbital error is reduced by processing at the gross over point.

The obtained results allowed us to correct the Jason-1 datasets which we dispose from the differences between the apparent sea level as measured by the altimeter and the true mean sea level. The corrected 250 cycles of altimetric Jason-1 tracks measurements of Sea Stat Bias effect, environmental and geophysical effects and orbital error permit us the determination of mean sea surface height (ssh) over the Western Mediterranean Sea.

The obtained surface was used to determine the dynamic topography of the Western Mediterranean, which varies between -1.95 m and 1.81 m, and the determination of the variability of the sea which is 1.72 mm / year.

Seasonal and Inter-seasonal Variations of the Geostrophic Flow from Altimetry and GOCE

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Key to the determination of the Surface Geostrophic Currents (SGC) is a reliable estimation of the ocean Dynamic Topography (DT) that, in turn, requires reliable measurements of the Sea Surface Height (SSH) and an independent geoid. Nowadays it is possible to combine 20 years altimetry data with the most recent advances in the geoid determination (provided by the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission) to obtain a mean DT with an unprecedented precision and accuracy. At the same time the improved accuracy in satellite altimetry data allows us to determine weekly SSH maps, and therefore a study of the time variations of the SGC based only on satellite data. In this work we combine monthly estimations of the SSH provided as a merged solution from several altimetric satellites (T/P, Jason-1/2, ERS-1/2, ENVISAT) with an independent solution (time-wise method) of the geoid provided by the third generation of GOCE data. From these data we determine a monthly map for the absolute DT, spanning from late 1992 to late 2010, with a resolution close to 111 km at the Equator. These maps are then used to derive the SGC. The time variations of the SGC are studied by two separated components: the seasonal and the inter-seasonal components. As expected, the Equator band and the major current areas are shown with the higher variability particularly for the zonal component. Nevertheless, only the Equatorial band shows a strong seasonality in SGC, whereas the middle latitudes see mostly higher-frequencies variability. The strong seasonal cycle at the Equator band (around 30 cm/s of amplitude for the zonal component) only suppose the 30-50% of the variability of the flow. The inter-annual variations revealed after removing from the data the seasonal cycles are, as expected, found to be strongly related with ENSO in the sequence of El Niño and La Niña events.

Meridional Rossby Wave Fronts and Vortices from AVISO Altimeter Data

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Satellite altimetry redefined the observation of oceanic Rossby waves in the last two decades. The release of multi–mission merged data sets furthered these advances as it permitted the observation of meso to large scale vortices. The propagation speed of some of these vortices is, both from theory and observations, similar to that of long 1st mode baroclinic Rossby waves. Several methods have been proposed to make the distinction between waves and vortices, generally based on kinematic properties of these closed, near–circular features. The present study makes use of a different approach and focuses on the physics of the waves instead of that of the vortices. More specifically, wavelengths and phase speeds for a set of periods are used to build a chain of finite impulse response filters. These filters are applied to zonal–temporal fields of sea surface height anomaly data from AVISO. In that, the seasonal signal and other low frequency basin–scale signals are separated upfront. The remainder is separated into wide spectral bands of westward–propagating signals with periods centred at 24, 12, 6, 3, and 1.5 months. These components are orthogonal and when added can reconstitute most of the original signal, with a residual dominated by small–scale random noise. The filter chain is applied independently at each latitude and oceanic basin. The phase speed is derived via Radon transform, and the wavelength and period from least squares fit. The filters are redesigned iteratively until the phase speed converges to a stable value. The meridional limits are set based on the critical latitude for each frequency band. The westward–propagating signals obtained by this method travel at Rossby wave phase speed, yet a clear distinction between a wave and a group of equally spaced vortices is not possible from the zonal–temporal data. To that effect the data are reorganised into maps. Each map corresponds to a week of sea surface height anomaly whose spectral content is constrained to a band of frequencies, wavelengths, and phase speeds that conform to the definition of Rossby waves. Although each latitude was processed independently, meridionally organised patterns are clearly observed in all basins. These patterns cannot be described as vortices as they form series of wave fronts with the meridional length scale significantly larger than the zonal length scale. Analysis of a temporal sequence of maps show these wave fronts progressing westward. However, as both phase speed and wavelength decrease poleward, the meridional alignment is not perfect and breaks often. Next, all these Rossby wave–like signals were added to produce one broad band signal, and from that maps were assembled in sequence and analysed. Surprisingly, the meridionally elongated patterns are no longer clear. Instead, many more vortices are visible and some can be visually tracked for tens of degrees. Two main conclusions derive from these observations. One is that the Rossby wave fronts are not an artifact of the filter. The other is that the combination of wave fronts is able to produce vortices.

Poster Session: Oceanography – Mean Sea Level Trends

Sea Level and Ocean Circulation in the high latitude seas and the Arctic Ocean

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Adopting an Earth system approach the EU FP7 MONARCH-A project is providing tailored information and products to assist climate change research. The information package is based on generation of time series of observation datasets and reanalyses enabling adequate descriptions of the status and evolution of the high latitude and Arctic region Earth system components, notably: (i) changes in carbon-water interaction; (ii) changes in sea level and ocean circulation; and (iii) changes in marine carbon cycle. This presentation will highlight findings and achievements regarding the sea level and ocean circulation in the high latitude seas and Arctic Ocean. Firstly, using updated fields of the mean sea surface in the high latitude and Arctic Ocean derived from altimetry and tide gauges together with the latest best estimate of the geoid derived from the GOCE satellite a new mean dynamic topography is reconstructed. This field displays a range of characteristic large scale shapes and features qualitatively in consistence with a priori knowledge. In addition a topographic high is clearly depicted in the Beaufort Gyre, in agreement with recently reported new findings from other complementary observation fields. Secondly, assessment of this observation based mean dynamic topography to fields derived from atmospherically forced ocean model reanalyses furthermore provides a mean to quantitatively examine the large scale ocean circulation and transport of heat and mass between the Northeast Atlantic and Arctic Ocean. Thirdly, these findings and results will be considered in the context of impact of changes in the mean sea level due to the Greenland Ice sheet mass changes and changes in freshwater run-off.

Tide Gauge-based Sea Level Variations Since 1950 along the Norwegian and Russian Coasts of the Arctic Ocean

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We investigate sea level change and variability in part of the Arctic region over the 1950-2009 period. Analysis of 62 long tide gauge records available during the studied period along the Norwegian and Russian coastlines shows that coastal mean sea level (corrected for Glacial Isostatic Adjustment and inverter barometer effects) in these two areas was almost stable until about 1980 but since then displayed a clear increasing trend. Until the mid-1990s, the mean coastal sea level closely follows closely the fluctuations of Arctic Oscillation (AO) index, but after the mid-to-late 1990s the co-fluctuation with the AO disappears. Since 1995, the coastal mean sea level (average of the Norwegian and Russian tide gauge data) presents an increasing trend of ~4 mm/yr. Using in situ ocean temperature and salinity data down to 700 m from three different data bases, we estimated the thermosteric, halosteric and steric (sum of thermosteric and halosteric) sea level since 1970 in the North Atlantic and Nordic Seas region, as well as along the Norwegian coast (incomplete data coverage prevented us to analyze steric data along the Russian coast). We note a strong anti-correlation between the thermosteric and halosteric components both in terms of spatial trends and regionally averaged time series. The latter show a strong change as of ~1995 that indicates simultaneous increase in temperature and salinity, a result confirmed but the Empirical Orthogonal Function decomposition over the studied region. Regionally distributed steric data are compared to altimetry-based sea level over 1993-2009. Spatial trend patterns of observed (altimetry-based) sea level over 1993-2009 are largely explained by steric patterns, but residual spatial trends suggest that other factors contribute, in particular regional ocean mass changes. Focusing again on Norwegian tide gauges, we compare observed coastal mean sea level with the steric sea level and the ocean mass component estimated with GRACE space gravimetry data (since 2003) and conclude that the mass component plays a non significant role and partly explains the sustained sea level rise (of ~4 mm/yr) observed over the altimetry era in that particular area.

Multi-model Reliability Estimates of Decadal Sea-level Trend Hindcasts

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Sea level future evolution is of primary importance in several sectors of our societies. For example, the work presented here is part of a French project aimed at evaluating impacts on coastal erosion in several French regions, including overseas (see http://www.anr-cecile.fr/). Reliability of projections for the next decades (also called "near term" in the CMIP5 exercice) must therefore be evaluated carefully prior to evaluating such impacts. Our focus here is on the reliability of basin scale regional patterns of sea level projections, beyond the global long-term trend over the last 50 years.

The primary data used is the set of retrospective decadal hindcast ensembles produced in the framework of CMIP5, both initialised with ocean reanalyses and uninitialized (20th century simulations with all forcings). The problem arises with observational datasets for forecast verification. Here, most sources of sea level are used to assess hindcasts, either direct or indirect observations: accurate continuous quality controlled tide gauge records, several reconstructions based on these, ocean reanalyses of temperature and salinity, precise altimetry since 1992. In this paper, we show different estimates of reliability of decadal trend hindcasts, and the gain of initialised over uninitialized historical forced hindcasts. We also measure the gain of using several models with respect to single model in the estimation of reliability. This is assessed with indirect observations, which are available continuously and globally, although they bear uncertainties in some regions. Using direct observations, we show that calibration using tide gauges improves hindcast reliability over the altimetry era.

Timescales for Detecting a Significant Acceleration in Sea-level Rise

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There is observational evidence that global mean sea levels (MSL) are rising and there is considerable concern that the rate of rise will accelerate throughout the 21st century, significantly threatening coastal communities. Early detection of a significant increase in the rate of sea-level rise is crucial, particularly if it is at the postulated higher rates of sea level rise. However, while we: (i) have high confidence from paleo sea level data and from a few long tide gauge records that there was an increase in the rate of mean sea level rise (MSLR) during the late 19th and early 20th centuries; and (ii) are virtually certain from tide gauge and radar altimetry observations that global MSL has risen over the 20th century at average rates of 1.7mm/yr and at rates almost double that (3.2mm/yr) since 1993; there still appears to be uncertainty regarding two related questions which have caused some to doubt the comparatively large rises in MSL projected over the course of the 21st century. First, is there evidence for significant acceleration in MSL since early in the 20th century or are observed changes since then essentially linear? Second, are the recent high rates of rise measured by radar altimetry since 1993, significantly larger than rates observed at other times in the 20th century? In this paper we examine both of these questions. First, we expand on each, by briefly reviewing the relevant literature. Then we attempt to provide fresh insight into the discussion by applying the methods that have tended to be used in the past to identify MSL accelerations (i.e. fitting quadratic trends and overlapping linear trends), to synthesized annual MSL time series, created by combining tide-gauge records or global reconstructions up to present with different projections of MSLR for the present time up to 2100.

Sea Level Reconstruction: Exploration of Methods for Combining Altimetry with Other Data to beyond the 20-year Altimetric Record

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Ocean satellite altimetry has provided global sets of sea level data for the last two decades, allowing determination of spatial patterns in global sea level. For reconstructions going back further than this period, tide gauge data can be used as a proxy for the model. We examine different methods of combining satellite altimetry and tide gauge data using optimal weighting of tide gauge data, linear regression and EOFs, including automatic quality checks of the tide gauge time series. We attempt to augment the model using various proxies such as climate indices like the NAO and PDO, and investigate alternative transformations such as maximum autocorrelation factors (MAF), which better take into account the spatio-temporal structure of the variation.

Whereas a traditional EOF analysis tries to explain as much variance as possible, the MAF transform considers noise to be uncorrelated with a spatially or temporally shifted version of itself, unlike the desired signal which will exhibit autocorrelation. This will be applied to a global dataset, necessitating wrap-around consideration of spatial shifts.

Parameters from physical oceanography will be incorporated using the SODA ocean model for a preliminary reference. We will attempt to take into account the uncertainties on thermosteric expansion and on ice sheet contributions.

Our focus is a timescale going back approximately 50 years, allowing reasonable global availability of tide gauge data. This allows for better sensitivity analysis with respect to spatial distribution, and tide gauge data are available around the Arctic Ocean, which may be important for a later high-latitude reconstruction.

The 2011 La Niña: So Strong, the Oceans Fell

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Global mean sea level (GMSL) dropped by 5 mm between the beginning of 2010 and mid 2011. This drop occurred despite the background rate of rise, 3 mm per year, which dominates most of the 18-year record observed by satellite altimeters. Using a combination of satellite and in situ data, we show that the decline in ocean mass, which explains 60 % of the sea level drop, coincides with an equivalent increase in terrestrial water storage, primarily over Australia, the Amazon basin, and Southeast Asia. This temporary shift of water from the ocean to land is closely related to the transition from El Niño conditions in 2009/10 to a strong 2010/11 La Niña, which affected precipitation patterns world-wide. The excess transport of water from the ocean represents a 3 % increase over the long-term climatological value. This study presents the first direct observation of the ENSO-induced exchange of freshwater that drives interannual changes in GMSL. Understanding these short-term changes helps to separate natural variability from anthropogenic and will ultimately provide a foundation for improved sea level predictions.

Global and Regional Sea Level Change

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Sealevel variations prior to the launch of satellite altimeters are estimated by analysing historic tide gauge records. Recently, a number of groups have reconstructed sea level by applying EOF techniques to gappy data. We complement this study with alternative methods. In a first step gaps in 178 records of sea level change are filled using the pattern recognition capabilities of artificial neural networks. Afterwards satellite altimetry is used to extrapolate local sea level change to global fields. Patterns of sea level change are compared to prior studies. Global mean sea level change since 1900 is found to be on average 1.79 mm per year.

Recent Change of thermosteric sea Level and its Contribution to the sea Level Change measured from Satellite Altimetry

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Sea level rise is global concern because it can impact on human lives and is a good indicator of climate change. Based on the analysis routinely performed by Japan Meteorological Agency (JMA), the global mean sea level rise at the rate of 3.0 mm/yr is observed by satellite altimeter from 1993 to 2010. Thermal expansion (thermosteric sea level change) is one of major factors that cause sea level change and the 0-700 m subsurface temperature change contributes 0.9 mm/yr in JMA routine analysis. Although the altimetry observed sea level rise is comparable with the rate during 1993-2003 reported in IPCC AR4, the thermal expansion is slightly smaller. Since 2003, the thermal expansion shows less increase than before although the sea level continues to rise. On the other hand, the geographical distribution of thermal expansion shows similar pattern to the sea level change. Comparing these data, the recent change of thermal expansion and its contribution to sea level rise will be discussed.

Advances in Climate Monitoring Using a Consistent Sea Level Record from 1900 to Present

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Studying past climate variations is vital to improving the understanding of current and future climate change. In order to make adequate comparisons between past and present climate variations, a long and consistent data record is necessary. Although sea level measurements provide an excellent indication of the state of the ocean, forming a sea level record that meets the requirements of sufficient duration, continuity and quality is a challenge. An inability to seamlessly and consistently marry the satellite altimetry record of the past two decades with the tide gauge record of the past century has restricted the ability to monitor the changing climate using the best measurements available at each point in time. To overcome the respective shortcomings of tide gauges and satellite altimetry, sea level has generally been reconstructed by combining the shorter but essentially complete global coverage offered by satellite altimetry with the longer but sparsely distributed tide gauge dataset. Such sea level reconstructions suffer from a decreasing number of tide gauges back through time and questions remain as to how well known climate signals are resolved. Previous reconstruction studies have focused on global mean sea level (GMSL) and the regional distribution of sea level trends with little discussion of the large-scale climate variability. Checking the degree to which known climate signals are resolved is one of the best validations of a sea level reconstruction.

Here, we present results using a consistent sea level record from 1900 to present derived from a sea level reconstruction based on cyclostationary empirical orthogonal functions (CSEOFs). We show how this reconstruction advances our understanding of the sea level signals associated with the large-scale ocean phenomena such as the seasonal signal, ENSO and longer time-scale signals like the Pacific Decadal Oscillation (PDO). Using our ability to capture large-scale climate signals and with the longer time series resulting from the reconstruction, we further investigate recent studies that have attributed downturns and upswings in global mean sea level to signals like ENSO and the PDO. Traditionally, a stationary annual cycle is removed from GMSL prior to computing trends and analyzing inter-annual variability. We show, however, that by not accounting for modulation in the strength of the seasonal signal over time, the apparent effect of ENSO on GMSL is enhanced and can lead to misinterpretations of the influence of ENSO on trends in GMSL. For large events such as the 1998 El Nino, ENSO can contribute short-term trends to GMSL approaching 4 mm/year. By separating the modulated annual cycle, ENSO and the PDO from GMSL and regional sea level, we can obtain better estimates of trends at global and regional scales over both the full time period of the reconstruction and the satellite altimeter era.

Error Characterization of the Global and Regional Mean Sea Level Evolution for Climate Applications.

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With the satellite altimetry missions, the global mean sea level (GMSL) has been calculated on a continual basis since January 1993. 'Verification' phases, during which the satellites follow each other in close succession (TOPEX/Poseidon--Jason-1, then Jason-1--Jason-2), help to link up these different missions by precisely determining any bias between them. Envisat, ERS-1 and ERS-2 are also used, after being adjusted on these reference missions, in order to compute Mean Sea Level at high latitudes (higher than 66°N and S), and also to improve spatial resolution by combining all these missions together.

The global mean sea level (MSL) deduced from TOPEX/Poseidon, Jason-1 and Jason-2 provides a global rate of 3.2 mm from 1993 to 2011 applying the post glacial rebound (MSL aviso website http://www.jason.oceanobs.com/msl). Besides, the regional sea level trends bring out an inhomogeneous repartition of the ocean elevation with local MSL slopes ranging from +/- 8 mm/yr.

Thanks to studies performed in the framework of the SALP project (supported by CNES) since the TOPEX era and more recently in the framework of the Sea-Level Climate Change Initiative (SLCCI) project (supported by ESA), strong improvements have been provided on the estimation of the global and regional MSL over all the altimetry periods for all the altimetry missions. Thanks to these efforts, a better characterization of the errors impacting the evolution of the global and the regional MSL has been performed. These errors concern different time scales as the long-term evolution (mean sea level trend) which is likely the most important scale for climate studies. Studies already performed have shown that the global MSL trend error is 0.6 mm/yr in a confidence interval of 90%. But other time scales are also of great interest for climate studies such as the inter-annual signal and other periodic signals (annual and semi-annual periods). Such errors could reduce the accuracy of the observation of the global MSL variations at these scales and can make it difficult to provide interpretation of geophysical mechanisms at the origin of these inter-annual signals.

In this paper, we propose to describe and quantified these errors as far as possible and discuss of their potential origin. The errors are also described in regards of the Climate User Requirements defined in the frame of the SLCCI project.

Estimating ENSO Influence on the Global Mean Sea Level During 1993-2010

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Interannual global mean sea level (GMSL) variations and El Nino-Southern Oscillation (ENSO) are highly correlated, with positive/negative GMSL anomalies during El Nino/La Nina events. In a previous study, we showed that interannual GMSL and global land water storage variations are quantitatively well correlated, with lower/higher than normal total water storage on land, and higher/lower GMSL during El Nino/La Nina,. Here, we investigate which oceanic regions (Atlantic, Indian and Pacific oceans) contribute to the interannual GMSL anomalies and focus on the 1993-2010 altimetry period including several El Nino and La Nina events. For each oceanic region, we compute the steric contribution (effect of temperature and salinity), and remove it from the mean sea level to estimate the mass component. We find that the tropical North tropical Pacific ocean (0°-30°N) mass is highly correlated with ENSO-related total land water storage. Analyses as a function of latitude/time and longitude/time show that tropical north Pacific mass excess is mostly confined within 10°N-20°N in the western half of the basin (120°E- 160°W). We computed the ocean-atmosphere water balance of the North Pacific and found that over the study period, the time derivative of the ocean mass component is well correlated with net P-E (precipitation minus evaporation). However during the 1997/1998 ENSO event, there is a temporary ocean mass increase, not compensated by the net P-E and likely due to an imbalance between the inflow/outflow entering/leaving the North Pacific. A qualitative analysis indicates that a significant reduction of the Makassar Strait transport, which accounts for 80% of the total Indonesian throughflow into the Indian Ocean, previously reported in the literature during the strong 1997/1998 El Nino event is consistent with the tropical North Pacific ocean mass excess.

Sixty years of regional sea level variability and its coastal impacts with focus on Caribbean Sea, South China Sea and Indian Ocean

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We investigate the regional sea level variability in the Caribbean, South China Sea and Indian Ocean in order to determine the total sea level change (i.e., global mean rise plus decadal/multi decadal variability) that has affected these regions since 1950. For this purpose, we make use of an EOF-based 2D past sea level reconstruction. This is a mean of 3 reconstructions based on few long tide gauge records available and different sea level grids from satellite altimetry and ocean circulation models like DRAKKAR and SODA. In the Caribbean Sea region, we find that over the past 60 years, the total climate-related sea level change is similar to the global mean rise (~1.8 mm per year) and that since the 1990s the interannual sea level variability has increased and is in good correlation with ENSO indices. Besides, we also note an increase in the number and intensity of hurricanes in the last two decades causing more negative impacts on the Caribbean coastal region than the sea level rise itself. Investigations in the South China Sea show that over the past 60 years, the rate of sea level rise is slightly higher than the global mean sea level. Along the coast of China, a region with shallow bathymetry, the rate of sea level rise is found to be twice as large as the global mean. By making use of GPS data in some areas of the studied regions, we also estimate the vertical land motions that superimpose to the climate-related sea level rise. Similar investigations on the regional sea level variability in the Indian Ocean are also presented.

Sea Level Rise and Subsidence in the Delta Areas of the Gulf of Thailand

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In frame of the Thailand-EC Co-Operation Facility GEO2TECDI project and follow-up project GEO2TECDI-SONG, we investigate the vertical land motion in Thailand and sea level change in the Gulf of Thailand. An important focus in this study is on Bangkok which faces a number of problems; 1) it is situated in a river delta and the average height is close to sea level, 2) it is subsiding due to ground water extraction, 3) it is experiencing co-seismic and post-seismic tectonic (vertical land) motion due to the mega-thrust Earthquakes in Indonesia, and 4) it suffers from rising sea level due to global climate change. This poses a serious threat to all dimensions of Thai society and economy, especially if you add the risk of excessive rainfall, which unfortunately recently became very real. Before hazard and damage mitigation methods can be devised all the contributing effects have to be charted, separated, qualified and quantified. For this we employ space geodetic techniques like GPS, interferometric SAR and satellite altimetry, and combine results with in situ observations from tide gauges and levelling. Adding GPS based vertical land motion to the tide gauge sea level registration reveals the absolute sea level change at a number of tide gauge stations surrounding the Gulf of Thailand, which is conclusively confirmed by satellite altimetry. In the Gulf of Thailand we find an average absolute rise of approximately 3.5 mm/yr ± 0.7, but near the estuaries of the Chao Praya River (Bangkok), the Kah Bpow River (Koh Kong) and the Mekong delta (Ho Chi Min City), this mounts to 4 to 5 mm/yr, definitely faster than the global average value. The situation worsens when taking into account the tectonic subsidence that resulted from the 2004 9.2 Mw Sumatra/Andaman earthquake; from 2005 onwards we find downfall in the order of 10 mm/yr resulting in relative sea level rise of >10 mm/yr over the last 5 years.

Long-Term Sea Level Change From Satellite Altimetry and Tide Gauges in the Indonesian Region

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We investigate the sea level rise in the Indonesian region in 1993-2011 based on satellite altimetry and tide gauges data. Satellite altimetry indicates a positive sea level rise in the entire Indonesian region higher than the global mean sea level rise. Values are between 2 and 4 mm/yr near four selected tide gauge stations.

Long-term trends of sea level at four tide gauge maintained by the Indonesian Coordinating Agency for Surveys and Mapping and at the co-located altimeter point are similar at only one station. Their differences at the other stations are attributed to the instability in the reference point of the station, which is possibly related to seismic activity and land. In Indonesia the determination of sea level change rate from tidal data is complicated because co-seismic displacements of the 2004 Sumatra Ardaman and following earthquake added vertical shifts that are still not accurately known into tidal data of all stations in the region. Other smaller jumps might be related to the local geodynamic activities.

The land vertical motion derived by GPS measurements of the German Indonesian Tsunami Early Warning System (GITEWS) project shows high vertical rates, that should be further confirmed by longer time-series. The instability in the reference level of the tidal records makes difficult to use tide gauge data for sea level change studies and altimetry data remains today the most promising database to estimate the absolute sea level rise around Indonesia.

Sea Level Changes in the Arctic Ocean

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Continuous monitoring of sea level variability from satellite altimetry can be considered as one of the most fundamental steps for a better understanding of oceanic processes in the deep ocean. For sun-synchronous satellites (e.g., ERS-2 and Envisat), the complexity of environments, such as extension of ice, corrupts altimetry measurements and limits their use in the Arctic Ocean (65º-90º).

In our presentation, the mean sea level trends from several ocean products DUACS (Data Unification and Altimeter Combination System), 'MyOcean' project and RADS Radar Altimeter Database System) are seen to give sea level trends in the Arctic that differs by several 100%. Even in areas with nearly no ice the difference is very considerably. As an example we calculated the mean sea level trend over the nearly ice-free region (30º-100º, 65º-80º). The mean sea level trend of 2.3 mm/yr, 3.2 mm/yr, 2.2 mm/yr are obtained from DUACS, MyOcean, RADS data sets over the regions, respectively.

Another example is the high sea level trend in the Beaufort Sea from DUACS and 'MyOcean' data sets affects the determined mean sea level trend significantly. In order to perform an independent comparison where all models have full coverage, here the first results using a new re-tracked ERS-2 data set is combined with a new improved and reprocessed ENVISAT dataset is presented.

Determining and Modelling Sea Level Change in the Caribbean Using Satellite Altimetry

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University of the West Indies, TRINIDAD AND TOBAGO

Sea level change is of major concern internationally, and it is especially significant for small island states, like those in the Caribbean. Small island states are amongst those that are most at risk from the effects of climate change and sea level rise, largely due to their environmental and economic dependence on coastal zones. Previous studies have been conducted in an attempt to investigate and monitor sea level rise in the Caribbean using in-situ tide gauges. However, these studies were incomplete and deficient owing to limitations in the tide gauge data reliability, incoherent time series and a lack of data coverage for the Caribbean region.

The research presented applies Jason-1 and Jason-2 data to the determination of sea level change in the Caribbean region. Estimates of sea level anomalies were determined for the period 2001 - 2010, through the application of a series of geophysical and atmospheric corrections. The altimetry data was then calibrated using an indirect method of altimetry bias determination that involved the use of Caribbean based tide gauges. A linear regression model was applied to the calibrated sea level anomalies to determine the rate of sea level change resulting in a gridded field of sea level change velocities for the Caribbean. The resulting altimetric derived sea levels were compared to eight existing tide gauges in the Caribbean.

Results revealed that some variations between the method of satellite altimetry and tide gauges do exist, however satellite altimetry sea level anomalies are shown to agree with a mean of 3.31 cm at the eight tide gauge comparison points. The sea level change rates presented are on average ± 0.45 mm/yr within the tide gauge derived rates. The derived sea level change model had a formal error of ± 0.39 mm/yr and an error budget of ± 0.65 mm/yr. These results demonstrate the viability of satellite altimetry as a technique to determine sea level change in the Caribbean, and is encouraging for future research and application in the region.

Poster Session: Oceanography - Mesoscale

Objective Identification and Tracking of Mesoscale Eddies

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Identification and tracking of mesoscale eddies in the ocean based on satellite altimetry measurements are broadly done using Eulerian methods. Such methods have two important shortcomings: 1) they are based on an idea of transport valid only for steady flows; and 2) they are tied to a particular reference frame choice. Here we introduce a Lagrangian method, referred to as ***geodesic method***, which is free of these shortcomings. The geodesic method is rooted in Haller and Beron-Vera's (2012) geodesic theory of transport barriers in unsteady two-dimensional flows. The geodesic theory objectively (i.e., in a frame-independent fashion) identifies transport barriers which shape global mixing patterns as material curves closely shadowed by least-stretching material curves. The geodesic method associates eddy boundaries with closed such transport barriers along which an appropriate Lagrangian shear measure is maximized. The rationale behind this is that, being weakly deforming, such closed shear-type transport barriers (generalized Lagrangian Coherent Structures or LCSs) are distinguished inhibitors of transport. Using altimetry measurements in the South Atlantic, we demonstrate that, unlike the widely used Eulerian methods, the geodesic method is capable of correctly locating and tracing coherent Agulhas Current rings.

Forecasting Sudden Changes in the Shape of the *Deepwater Horizon* Oil Spill using LCS-core Analysis

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We present a methodology to predict major short-term changes in environmental contamination patterns, such as oil spills in the ocean. Our approach is based on new mathematical results on the objective (frame-independent) identification of key material surfaces that drive tracer mixing in unsteady, finite-time flow data. Some of these material surfaces, known as Lagrangian Coherent Structures (LCSs), turn out to admit highly attracting cores that lead to inevitable material instabilities even under future uncertainties or unexpected perturbations to the observed flow. These LCS cores have the potential to forecast imminent shape changes in the contamination pattern, even before the instability builds up and brings large masses of water into motion. Exploiting this potential, the ***LCS-core analysis*** developed here provides a model-independent forecasting scheme that relies only on already observed or validated flow velocities at the time the prediction is made. We use this methodology to obtain high-precision forecasts of two major instabilities that occurred in the shape of the *Deepwater Horizon* oil spill as observed in surface ocean images. This is done using surface ocean currents produced by the data-assimilative Navy Coastal Ocean Model and assuming that the oil behaves as a passive tracer.

Southwestern Atlantic Ocean: Estimating the Eddy Kinetic Energy and Momentum Flux Fields from Altimetry

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The mean surface energetics of the Southwestern Atlantic Ocean is studied here through the analysis of 20 years of altimetry data from AVISO. The mean geostrophic velocities are obtained by the difference between the absolute geostrophic velocities and the geostrophic anomaly velocities, from the 1/3° gridded Ssalto/Duacs delayed-time updated (with four satellites) altimeter product of AVISO. This product uses data for nineteen years of sea level fields (from October 1992 to July 2011). The Eddy Kinetic Energy (EKE) budget requires a good estimate of EKE itself, thus leading to a reliable computation of the barotropic conversion processes in the ocean. The EKE field is normally associated with mesoscale activity. Eddy processes play two important roles in the mean kinetic energy (MKE) balance, i.e., they influence the kinetic energy conversion and the kinetic energy redistribution. The highest EKE was found in the vicinity of the Brazil-Malvinas Confluence, with values of approximately

$1500\ cm^2\ s^{-2}$. The EKE reaches values lower than $250\ cm^2\ s^{-2}$ and $50\ cm^2\ s^{-2}$ along the path of the Brazil Current (BC) and into the ocean interior, respectively. The ratio between MKE and EKE shows values greater than the unity, i.e., MKE > EKE, for the most of the BC's path, while the EKE dominates the ocean interior. Comparing this ratio with the distribution of the eddy momentum fluxes, one can get insight into whether eddies are formed locally or if they drift with the background flow. In the southestern Atlantic, the eddy momentum flux has its positive maximum along the axis of the BC and at the area of the South Atlantic Current (SAC). Furthermore, the eddy momentum flux is very close to zero outside the axis of the CB and SAC, and the observed EKE in the ocean interior cannot be generated locally. The eddies generated close to these currents and advected to the interior ocean. Finally, at least for most of the BC path, the EKE is generated locally since the eddy momentum flux is high and positive.

Eddy Activity at Three Major Southern Hemisphere Western Boundary current Systems from Satellite Altimetry.

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Between January/1993 and December/2008 mesoscale oceanic eddies shed by three major Southern Hemisphere western boundary currents systems were studied for their type (warm or cold), length, lifetime, propagation distance and frequency of occurrence. The data was obtained from an eddy tracking dataset (Chelton et al.,2011, Progress in Oceanography) developed after sea surface height (SSH) AVISO Reference fields, comprising of TOPEX/Poseidon (and subsequently Jason-1 and 2) and ERS 1-2 (followed by Envisat) altimeters data. This unified dataset has a higher spatial resolution than those presented in previous studies, allowing the resolution of oceanic features of 40 km of length or higher. This high spatial/temporal coverage of the global oceans turns SSH merged altimeter data into a unique tool for studying mesoscale variability. Areas of higher Eddy Kinetic Energy (EKE) associated to the separation latitudes of the East Australian Current (EAC), the Agulhas Retroflection (AR) and the Brazil-Malvinas Confluence (BMC) were selected. The eddies were divided into two groups with respect to their mean diameter: (i) large eddies, defined as all features larger than the mean plus one standard deviation, and (ii) small eddies, defined as all features measuring less than the mean minus one standard deviation. In all three systems the studied eddies presented geographical segregation according to their spatial scales. A total of 148 large eddies were shed by the EAC during the 16 years period, mainly between 24ºS and 38ºS, presenting a distribution associated with the EAC separation points from the coast. The 131 small eddies associated to the same current concentrated in the South Tasman Sea, from 35ºS to 48ºS. After leaving Tasmania southern coast, a small anticyclonic eddy propagated 3.788km westwards up to 122ºE. At the BMC, while 98 large eddies were identified between 35ºS and 42ºS, 87 smaller ones seemed to follow the counterclockwise rotation induced by the Zapiola Anticyclone at higher latitudes (between 42ºS and 50ºS). This pattern was not identified by previous eddy census in this region, which were performed with a single altimeter dataset instead of the merged data used here. At the AR region the most pronounced difference between large and small eddies is their propagation distance and lifetime. About 20% of the 191 large eddies crossed the Mid Atlantic Ridge along their westward propagation and four of those eddies reached the Brazilian coast with radii larger than 40 km. Only anticyclonic eddies reached the Brazilian coast, while the cyclonic ones were limited to 30ºW. While the presence of Walvis Ridge did not seem to affect AR large eddies, it seems to be a geographical constraint for the dissipation of the 178 smaller eddies. Eddies frequency, length, lifetime and propagation distance have not presented any significant temporal trend and these characteristics are being subject to further investigation.

Probability Density Functions And Higher Order Statistics of Large-Scale Geostrophic Velocity Estimates And Sea Surface Height

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We show geostrophic velocity Probability Density Functions (PDF) for both velocity components, u and v, estimated from the 3-year long Jason-1 - TOPEX/Poseidon (JTP) Tandem Mission which allow to infer both velocity components directly from the altimeter observations. In order to combine previous results of velocity- and SSH-PDF we included in our analysis the 18.5-year time series of SSH from the TOPEX/Poseidon, Jason-1 and Jason-2 (TPJJ) missions as well. The differences in the zonal and meridional components are found to be evident, with a wider shape for the zonal velocity component due to the larger variability in zonal direction. Our results confirm that the exponential shape of the global velocity PDF is a consequence of the spatially inhomogeneous EKE distribution over the global ocean. Regions that only have a small variance in EKE, have a gaussian shaped PDF. Accordingly, normalizing any regional velocity PDF with their standard deviation also results in a gaussian PDF. Using both geostrophic velocity components, it has been possible to calculate the PDF-width (w), which is equivalent to the RMS velocity or the EKE. To further describe the behavior of the PDF, the skewness and kurtosis are calculated for the first time for both velocity components and for the SSH. Skewness and kurtosis are statistical parameters that can be used to infer the deviation of a distribution from the Gaussian, as seen in recent studies. Also, it is a mean to reveal geographical pattern of the eddies in the global oceans, e.g. identify the mean path of unstable ocean jets as well as regions dominated by eddies. Specifically we investigate the seasonal changes of skewness and kurtosis from the 18.5-year SSH time series of TPJJ. The seasonal distribution of SSH-skewness indicates that e.g. the strong western boundary currents, evident as a dipole structure, are evident throughout the year, but with changes in the magnitude of the skewness. The same persistence can be seen in the structures of the kurtosis in the boundary current regions.

Temporal Change of Eddy Variability

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The temporal changes of the ocean's eddy variability and the underlying dynamical causes are investigated. Specifically, we revisit the question to which extent the eddy field is reacting to changes in the wind forcing. The study is based on a 18.5 year long time series of Sea Surface Height (SSH) anomalies (TOPEX/Poseidon, Jason-1, Jason-2), from which statistics for the eddy kinetic energy field (EKE) are computed. EKE fields are also computed from a high resolution, eddy-resolving global circulation model STORM, driven both by NCEP forcing and by climatological winds. The normalized temporal trends of SSH and EKE are used to infer decadal changes in eddy variability. Our results suggest that changes of EKE depicts a complex pattern and is far from uniform. A comparison of the time series of wind stress and EKE suggest that changing winds cause a response in eddy activity with a lag of 2 – 3 years on global average. However, there are several parts of the ocean where we can not find a direct relation between the wind forcing and the increase in EKE, which points to non-local forcing effects of eddy variability or other processes underlying eddy variability. On basin average, changes in eddy variability appear to be correlated with climate modes. STORM results are in very good agreement with altimeter results. The lag of maximum cross correlation of the wind speed and 30 year EKE derived from a eddy-resolution global model STORM are mostly positive but quite variable.

Ocean Eddy Effect on Atmosphere in Vicinity of Sea Surface Temperature Fronts

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Using the satellite observation data, the prominent heat advection effect by geostrophic currents of eddy on sea surface temperature (SST) have been found in two regions during winter monsoon, one is the continental slope area in the northern South China Sea and other is the Subtropical Countercurrent area in the North Pacific, where the SST front and eddy are stronger. The heat advection effect of eddy current significantly adjusts the SST spatial distribution: warms (cools) the sea surface in the west of anticyclonic (cyclonic) eddies, causing the cusp-shaped distortion of the SST front. Subsequently, sea surface wind becomes highly uneven in space: it blows faster (slower) over warmer (colder) SST regions than the surroundings. The SST and sea surface wind spatial non-uniformity due to the heat advection by eddy currents, shifts with eddy motion. These new findings based on satellite observations show oceanic eddy roles in ocean-atmosphere interaction on weather timescale.

Western Boundary Currents and Associated Mesoscale Activity in the Solomon Sea as Observed from Altimetry and Gliders

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The Solomon Sea, with its intense Low Latitude Western Boundary Currents (LLWBCs), is a key region in the Pacific Ocean where equatorial and subtropical circulations are connected. This region exhibits the highest levels of sea level variability of the whole South Equatorial Pacific Ocean. We analyzed altimetric data to explore the variability of both the sea level and the western boundary current of this relatively poorly known part of the ocean. Specifically reprocessed along-track data have appeared especially helpful for documenting the fine structure of surface coastal currents. In addition, we used the standard gridded data SLA to document (1) the dominant periods of SLA variability, occuring at annual and interannual (ENSO) time scales, and (2) the high level of eddy kinetic energy that extends from the mouth of Solomon Strait to the central Solomon Sea. Moreover, high mesoscale activity develops in this region of extremely intricate geography, with numerous islands and complex bathymetry. Indeed, an experimental glider monitoring of the LLWBCs, operated since August 2007, shows huge variability of the transports in relation to ENSO conditions and eddy activity. To document the mesoscale activity and its variability, we analyze altimetric data together with the different glider missions operated in the Solomon Sea. Altimetric data gives in particular information both on cyclonic and anticyclonic eddies in term of density and its modulation at seasonal/interannual time scale, size, and intensity of the structures. The absolute geostrophic cross track current from the glider is timely well fitted by the altimetric circulation. We take advantage of this good consistency between the two data set: An eddy-tracking algorithm based on altimetric data is used to track the most energetic eddies in order to detect eddies crossed by gliders and so to document their vertical structures.

Monitoring of a Stationary and Seasonal Anticyclonic Eddy by Means of Remote Sensing Data

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Sea Level Anomaly (SLA) maps have been analysed for the southeastern corner of the Bay of Biscay, in order to monitor a stationary and seasonal anticyclonic eddy, within the period 2003-2010. The generation of this mesoscale structure, with an 80-100 km diameter, has been related to the intensification of the slope current and the interactions of the current with the topographic irregularities. Once generated, the eddy remains near the generation place, apparently

trapped by the topography. The altimetric data has been complemented with cloud-free IR and visible maps, with two objectives. First, Sea Surface Temperature (SST) and Chlorophyll-a (Chl-a) concentration maps have been used for obtaining near-coast measurements, necessary to investigate the generation area. Although the southeastern corner of the Bay of Biscay is covered by clouds for a great part of the year, and therefore it is difficult to find cloud-free images, the higher spatial and temporal resolution of SST and Chl-a maps, in comparison to altimetry, permits observation of the modifications of the slope current direction in relation to the topographic irregularities. Secondly, the SST and Chl-a maps have been used to validate the signal observed in the SLA maps, in a daily basis. Besides these remote sensing data, currents and sea level simulations from the ROMS numerical model, together with data from a coastal HF radar measuring surface currents in the study area since 2009, have been also used to validate the altimetric observations. Results indicate that this structure originates between Capes Mayor and Ajo and Cape Breton canyon after a major change in the slope and in the direction of the slope current. This anticyclonic eddy is originated every year (2003-2010), describing a seasonal pattern: it is generated at the end of winter, beginning of spring and it remains almost in the same position until the beginning of autumn. From October to the end of winter, a cyclonic circulation dominates the study area.

On the Joint Use of High Resolution Tracer Images and Altimetric Data for the Control of Ocean Circulations

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Over the past two decades, altimetric satellites unprecedently observed turbulent features of ocean dynamics at the mesoscale. High resolution sensors of tracers such as the Sea Surface Temperature or the Ocean Color reveal even smaller structures at the submesoscale, which are not seen by altimetry. The role of the submesoscale in the ocean may be very important for the dynamic at larger scales. Therefore, we must benefit from the two types of observations (mesoscale dynamic and submesoscale tracer image) to refine the estimation of the ocean circulation.

The goal of this study is to explore the feasibility of using tracer information at the submesoscales to complement the control of ocean dynamic fields that emerge from altimeter data analysis at larger scales. To do so, an image data assimilation strategy is developed in which a cost-function is built that minimizes the misfits between image of submesoscale flow structure and tracer images. In the present work, we have chosen as an image of submesoscale flow structure the Finite-Size Lyapunov Exponents (FSLE). The choice of FSLE as a proxy for tracers is motivated by d'Ovidio et al (2004), where similar patterns between tracers and FSLE images are evidenced.

A prerequisite to the study is that the relation between the ocean dynamics and FSLE can be inverted, in other words that the submesoscale information transmitted through the intermediate FSLE proxy is effective in controlling the ocean system. This assumption has been successfully tested on several regional pieces of the ocean. Using a strategy similar to the one used in Data Assimilation, the sensitivity of FSLE horizontal patterns to velocity errors is investigated. To do so, a Gaussian velocity error field is created using fifteen years of altimetric data. A cost function is then defined to measure the misfit between the FSLE computed using velocities with errors and the FSLE derived from a 'true' (error free) velocity. It is found that a global minimum can be identified in the cost function proving that the inversion of FSLE is feasible. The next step is the inversion of submesoscale tracer information to correct a mesoscale altimetric field using real observation. The ocean dynamical variable to be corrected is the mesoscale altimetric velocity field using a high resolution tracer image. The strategy is similar to the one used to invert FSLE. The cost function measures the misfit between the FSLE derived from the altimetric velocity and the high resolution tracer image. Several test cases have been studied and demonstrating the success of the inversion of submesoscale tracer information to correct a mesoscale altimetric velocity field.

These results show the feasibility of assimilating tracer submesoscales into ocean models for the control of mesoscale dynamics and larger scales as deduced from altimetry and therefore the benefit of the joint use of tracer image and altimetric data for the control of ocean circulations.

A New Census of Eddies in the Western Mediterranean Sea

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Eighteen years of weekly SLA merged maps in the Western Mediterranean are analyzed using the new method proposed by Chelton et al. (2011) to identify and track mesoscale eddies. Preliminary results confirm that eddies are smaller in radius and weaker in amplitude than in the global Ocean. There is, however, a significant spatial variability of eddies characteristics, with larger and stronger features in the southern basin in agreement with the literature in the Western Mediterranean. As in the global Ocean, anticyclonic eddies tend to last longer than the cyclones. The propagation speeds and direction show a wide range of values without a clear preferred direction, although there is a certain west-east dominance. The temporal evolution of the weekly number of eddies is also examined presenting a small trend modulated by intraannual and interannual variability. These are preliminary results that need to be further developed to understand the dynamical processes that can explain the observed variability. Future work also includes performing a sensitivity analysis on the parameters of the method as well as improving the eddy identification close to the coast.

Recent Advances on Mesoscale Variability in the Western Mediterranean: Complementarity Between Altimetry and Other Sensors

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Satellite altimetry has provided a unique contribution to the global observation of mesoscale variability, the dominant surface signal in the ocean circulation at mid and high latitudes. In particular, it is now possible to quantify and monitor surface mesoscale eddies. However, the single use satellite altimetry only allows providing surface information with a limited spatio/temporal coverage. Thus, to circumvent these limitations and to fully understand the three-dimensional variability it is necessary to complement altimetry data with alternative remote and in-situ sensors.

In this study we review recent advances on mesoscale variability as seen by the synergy of altimetry and independent observations in the Western Mediterranean, where the circulation is rather complex due to the presence of multiple interacting scales, including basin, sub-basin scale and mesoscale structures. The challenges of characterizing these processes imply therefore precise and high-resolution observations in addition to multi-sensor approaches. Accordingly, multi-platform experiments have been designed and carried out in the different sub-basins of the Western Mediterranean Sea highlighting the need of synergetic approaches through the combined use of observing systems at several spatial/temporal scales, with the aim of better understanding mesoscale dynamics.

Interannual Variability of Eddy Kinetic Energy in Three Major Western Boundary Currents Systems of the Southern Hemisphere

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Western boundary currents (WBC) play an essential role in Earth's heat distribution and climate. In the subtropical gyres, the regions where the WBCs leave the coastline to become free jets in the ocean are normally associated with much larger Eddy Kinetic Energy (EKE) values than the ocean interior. Those larger EKE fields result from strong mesoscale activity in those areas. Moreover, an accurate estimate of the EKE is instrumental to calculate the EKE budget, thus leading to reliable estimates of the barotropic conversion processes present in a given ocean area. The EKE fields respond to the ocean circulation variability and thus to the climate system itself.In the Southern Hemisphere, modes of climate variability such as El Nino Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) should be important players in the modulation of the WBCs variability and thus the associated EKE fields. This study focus on the correlations between those climate modes and the interannual EKE fields associated to the retroflection zones of the Brazil, Agulhas and East Australian Currents. The temporal trends on those EKE fields are also presented and discussed. For each current, the EKE field was built from velocity anomalies data (u' and v') calculated using the satellite altimetry maps of sea level anomaly dataset (MSLA) provided by AVISO spanning from 1992 to 2011. The modes of variability indices were obtained from the NOAA Predication Climate Center (CPC). Despite different rates for the last 20 years, the EKE fields estimated for all WBCs currents systems considered showed positive linear trends. While the Brazil and the Agulhas Currents presented EKEincreasing at rates of 0.24(cm^2/s^2.month) and 0.22 (cm^2/s^2.month) significant at 95% level, respectively, the East Australian Current presented a much smaller trend of 0.02 (cm^2/s^2.month). EKE correlation with the Nino 3.4 index is positive (0.3). Significant correlation (-0.3) at zero-lag was found between the Brazil Current system, which showed an increase in EKE during the last 20 years, and the SAM index that had a negative trend throughout same period. Conversely, at zero-lag the Agulhas Current EKE was significantly correlated only to the Southern Oscillation Index (SOI) (0.3), which also shows a positive trend over the last two decades.

Validation of Eddies Representation in the Mercator Océan Global Eddy-resolving Model (1/12) with Altimetry estimates.

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In 2007, Mercator Océan has initiated for operational oceanography application the development of a global ocean/sea ice high-resolution model (1/12°), based on the NEMO OGCM. The last experiment has been driven over the last decade (2000-2009) by the ERAinterim reanalysis fluxes. In order to better capture high frequency variability, the upper layers are well resolved with 1 meter vertical resolution at the surface and 20 layers in the first 60 meters depths, the atmospheric forcing is sampled to 3H with a diurnal cycle applied to the downwelling shortwave radiative atmospheric forcing.

First, we present a validation of the dynamics represented by the model with the altimetric data. The western boundary currents are particularly well represented in terms of magnitude and pathways (Gulf Stream). We show also the gain obtained by the use of the high horizontal resolution compared to a twin experiment performed at eddy permitting resolution at 1/4° horizontal resolution: for example, difference with altimetry of the root mean square of the sea surface height is reduced by 50% at 35°N.

Then, a particular focus is made on the ability of the 1/12° model to simulate the mesoscale activity via the representation of eddies. This study is performed on the model surface fields with an original eddy detection and tracking software based on the Okubo Weiss criteria. The results, in term of eddies number, eddies lifetime and eddies trajectories, are favorably compared with the altimetry estimates counterpart: between 50ºS and 50ºN, results are in good agreement with eddies detected by Chelton et al. (2011) on AVISO maps.

Global Variability of the Wavenumber Spectrum of Oceanic Mesoscale Turbulence- Revisited

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The wavenumber spectrum of sea surface height (SSH) observed by satellite altimetry was analyzed by Xu and Fu (Journal of Physical Oceanography, Vol. 41, 802-809, 2011). The spectral shape in the wavelength range of 70-250 km was approximated by a power law, representing a regime believed to be governed by geostrophic turbulence theories. The estimated spectral slope was mapped globally, revealing geographic variability similar to the variability of the mesoscale energy level. In this study, the effects of the measurement noise on the spectral slope estimate are examined. Using nearly simultaneous observations made by Jason-1 and Jason-2 during their cross-calibration phase, we found that the while noise level of altimetry measurement was best estimated from the spectral values at wavelengths from 25-35 km. After removing a white noise level based on such estimate from the SSH spectrum, we found that the spectral slope values had changed significantly over some regions. We thus re-mapped the global SSH spectral slope from the new calculations. The qualitative pattern of the global variability has not changed, but the slopes have generally become steeper than the previous estimates. In the high eddy energy regions, the slopes become slightly steeper, with more values less than -4. In the low eddy energy regions, the slopes become significantly steeper, with values less than -2 everywhere poleward of the 20 degree latitudes. The implications of the revised spectral slope estimates will be discussed in terms of ocean dynamics as well as outstanding issues in altimetry measurement.

Contribution from Altimetry to the Study of Meso and Submesoscale Oceanic Eddies: A Regional Application to the Bay of Biscay.

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The Bay of Biscay, in the North East Atlantic, is the scene of a particularly complex ocean dynamics in which the slope current plays a role in the development of (sub)mesoscale structures offshore, contributing to water exchanges between the continental shelf and the open ocean.

Thanks to long time series and its precision, altimetry is an ideal tool for the observation of such processes. Due to the regional dynamics, it is necessary to benefit from recent advances in coastal altimetry to study these dynamics. Methodological developments were thus required and their results were then analysed. The work presented here will thus focus on three main points:

- The development of an along-track wavelet analysis method to determine the observability of the (sub)mesoscale and to assess the validity of global maps of the sea level over this specific variability.
- The adaptation of the sea level mapping methodology to the regional fine scale variability. This method was put in place over a period of optimal spatial coverage with 4 satellites (2002-2005). Geostrophic velocities and Finite-Size Lyapunov exponents (FSLE) derived from these regional maps of sea level were then the subject of an intense validation using independent observations (currentmeters, drifting buoys, satellite images - sea surface temperature & ocean colour).
- The analysis of the regional meso and submesoscale variability: climatologies of the properties of these dynamics were computed and a combined analysis of regional sea level maps, satellite images and in-situ data was used to describe particular fine scale processes.

Regional (sub)mesoscale processes are currently under-evaluated in maps of the sea level. Fine-scale mapping can improve regional estimates of Eddy Kinetic Energy (EKE) levels and submesoscale variability (FSLE). In addition, the variability of the slope current is improved. A sequence of fine-scale eddy detachment from the slope current is made possible using a multi-sensor approach. Phase lags are observed between the continental slope and offshore variability of the meso and submeso-scale dynamics, supporting the role played by the slope current as a source of energy for offshore areas.

Finally, this study opens up the perspective of observations, including the provision of areas for the development of regional mapping methodologies and the improvement observational error budgets. These methodological developments can be extended to other regions and altimetry datasets. Regional maps provide an important observation for the interpretation of the Bay of Biscay ocean dynamics and for the validation of regional models. Further examples of the contribution of this work to regional (sub)mesocale studies will be presented for the Gulf of Mexico and the North-western basin of the Mediterranean.

Exploring the Observability of Altimetry from a High Resolution Numerical Model of the Salomon Sea

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The Solomon sea is a key region of the Pacific Ocean where low latitude western boundary currents connect equatorial and subtropical circulations and that are suspected to play an important role in the modulation of ENSO. This circulation exhibits the highest levels of sea level variability of the whole tropical Pacific Ocean, and they are characteristics of a large range of variability from interannual (ENSO) to seasonnal and mesoscales.

Because of its complex and intricate bathymetry, the numerous islands and narrow straits, the region raises specific challenges for altimetry data processing.

The SARAL/AltiKa upcoming space mission should provide more faithful products in the region because of its improved accuracy. Later on, SWOT should be of particular interest in the area. There is still much uncertainty on the signal that will be observed by SWOT, especially at the submesoscales. There are many scientific and technical questions that are still unresolved such as the observability of altimetry at very high resolutions and more generally the dynamical role of the ocean submesoscales that will become accessible with such future observations.

A high resolution numerical model (1/36°) of the Solomon sea has been developed to address this observability question. This model is two-way embedded in a 1/12° regional model which is itself one-way embedded in the DRAKKAR 1/12° global model. The NEMO code is used as well as the AGRIF software for model nestings. A first version of this model configuration has already been run at a lower resolution (1/12°) and was assessed with altimetric data.

In this work we propose a detailed analysis of the SSH properties provided by the high resolution model with regard to coarsest versions of the model in order to better assess the sub and mesoscale signal, and to explore the observability of altimetry to observe the high frequency signals in the Solomon Sea.

Jets, Rossby Waves and Eddies off California

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The analysis of SSH altimetry observations between 1992 and 2009 demonstrated that mesoscale flow off California presented a self-organized system of quasi-zonal jets, bi-annual oscillations, annual and semi-annual Rossby waves, as well as mesoscale eddies. This system was driven by near-resonance interactions between flow scales. Quartet (modulation) instability dominated and caused a non-local transferring energy from waves and eddies to bi-annual oscillations and quasi-zonal jets. The recognized mechanism required existence of a certain level of dissipativity in the flow.

Characterization of SSH and SST wavenumber Spectral Slopes over the global Ocean

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The wavenumber of sea surface height (SSH) from satellite altimeter observations over the global ocean have revealed complex spatial variability (Xu, 2011). The same analysis is carried out with satellite microwave radiometer SST data (AMSR-E). The global map of the spectral slopes of SST wavenumber spectrum in the wavelength band 70-250 km exhibit this regional variability with steeper slopes in high-energy regions and the seasonal global maps of cross-correlation between SST and SSH (in the wavelength band 70-250 km) also show high correlations in these regions.

A similar analysis is carried out with higher resolution (~ 1 km) satellite SST data to somehow confirm this regional variability at the higher wavenumber domain (< 80 km). However taking into account a noise correction for the SST spectral analysis, steeper wavenumber spectral slopes are found to be more homogeneous over the different oceanic basins. This study then question the exact slope of SST and SSH for the short mesoscale wavenumber region and a practical solution is applied to further analysed joined SST and SSH fields at higher resolution.

A 34-Year Historical and Altimetric Perspective of Loop Current Intrusion and Eddy Separation in the Gulf of Mexico

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Continuous altimetric monitoring of Loop Current intrusion and eddy separation in the Gulf of Mexico has been possible since ERS-1 was placed in the multidisciplinary 35-day repeat orbit in April 1992. In the 20-year time period since then a total of 30 major anticyclonic eddies have separated from the Loop Current, which gives an average separation period of 8 months over the continuous altimetric record. A recent reanalysis of the available satellite and industry observations back to July 1978 found 19 additional eddies giving a total of 49 separation events over the 34-year record or an average separation period of 8.4 months. The average separation period is thus relatively stable over the more than three decades of observation; nevertheless, the time interval between separation events is quite irregular, exhibiting a range from 2 weeks to over 18 months. Over a dozen dynamical mechanisms have been proposed to explain eddy separation; however, no Loop Current eddy separation precursor had been identified until Loop Current retreat following eddy separation was shown to be a good predictor of the subsequent eddy separation period. A simple Loop Current vorticity model provides a theoretical basis for this empirical relationship. After suitable scaling approximations, the theory predicts that the Loop Current separation period is a linear function of retreat latitude, which agrees well with altimeter-derived empirical results. The regressions results show that this relationship is statistically stable over the 34-year record, as would be expected of a physically controlled phenomenon. Other Loop Current statistics show similar stationarity. A histogram of separation times binned by month shows a clear seasonal signal in the monthly distribution with separation occurring more often in late winter/early spring and late summer/early fall, with "fall" separation events being 50% more likely than "spring". The stationarity of the Loop Current separation period and retreat latitude statistics, including the seasonality of the separation times, over the 34-year record is remarkable and is the most significant result found in this analysis of the historical and altimetric records. In honor of the 34-year anniversary of the launch of Seasat and the progress in radar altimetry, we will highlight satellite observations of the initial separation event in our record using Seasat synthetic aperture radar imagery and radar altimetry from July 1978.

The Wavenumber Spectrum of SSH in the Caribbean Sea

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Output from a high-resolution operational ocean model is compared with along-track altimetric SSH in order to understand processes governing the wavenumber spectrum of SSH, particularly the dual roles of tidal internal waves and mesoscale variability. The Caribbean Sea is the focus of study because it contains several internal wave generation sites and a relatively homogeneous mesoscale eddy field. Tides, while small, influence the SSH spectrum slope at scales smaller than 150km, with contributions from both the coherent (phase-locked) and incoherent internal tides. Causes and consequences of incoherent tides are diagnosed in the model with consideration of their role in the noise budget of future wide-swath altimeter missions.

Oceanic Energy Spectra and Fluxes at Mesoscale and Submesoscale

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Oceanic energy spectra and fluxes at mesoscale and submesoscale are examined with currents observed from multiple platforms off the U. S. West Coast [e.g., satellite altimeters (ALT), high-frequency radars (HFR), shipboard ADCPs] to illustrate the pathways of ocean energy between two scales. The one-dimensional wave-number spectra of HFR-derived surface currents agree with those of ALT-derived cross-track geostrophic currents at scales larger than 100 km, and decay with k^{-2} at high wave-number (less than 100 km), aligned with submesoscale spectra. Subsurface currents from shipboard ADCPs support continuous spatial scales in the energy spectra. Based the energy fluxes computed from gridded ALT-derived geostrophic currents, the length scale where an inverse cascade appears was nearly the Rossby deformation radius (e.g., 100 to 150 km at the mid-latitude region). This steering length scale to divide the direction of energy cascade (forward or inverse) is reported as approximately 15 to 20 km from HFR-derived surface currents.

Poster Session: Oceanography – Tides – Internal Tides and High Frequency Processes

Comparison of global and regional Tide Models using Data from Satellite Altimeters and Tide Gauges in the Northeast Sector

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Comparison of Global and Regional Tide Models using Data from Satellite Altimeters and Tide Gauges in the Northeast Sector of the Antarctic Peninsula.

A number of global and regional tide models have been developed and improved in the last decade with the purpose of obtaining the best correction to be applied to the satellite heights. It has been shown that these models are less accurate in coastal and polar areas, as Antarctica, than in other ocean areas.

An accurate knowledge of the tides in Antarctica is difficult because of the limited number and short duration of the tide gauge observations. However, since few years ago the number of observations in Antarctica is enough to get precise components of tide, especially in the Northeast Sector of the Antarctic Peninsula. This area is characterized by the presence of iceberg and rubble ice broken off from glaciers and Ronne-Filchner and Larsen ice shelves. In addition to this, parts of polar ocean are covered by permanent or seasonal sea ice. These conditions considerably limit the number of useful satellite altimetry data. In this work, a comparison of the latest global and regional tide models with available tide-gauge data is performed in the Northeast Sector of the Antarctic Peninsula. Observations of tide gauges are scarce, due to the fact that most of the Antarctic bases are located on the west coast of the Antarctic Peninsula and on the South Shetland Islands. For the chosen area a comparative analysis between the amplitudes and epochs of 8 components of tide (Q1, O1, P1, K1, N2, M2, S2, and K2) obtained from 44 intersections of T/P, Jason1 and Jason2 tracks and 3 conventional tide gauges versus 9 tide models: GOT4.7, TPXO7.2, FES2004, EOT08a, EOT10a, AOATLAS2011, ANTPEN, CATS2008 y CADA10 is performed. Results show that for the most important semidiurnal constituent M2, the smallest Root Mean Square misfits (RMSmisfit) correspond to models EOT08a, CADA10 and EOT10a (0.019m, 0.020m and 0.021m respectively). For the most important diurnal constituent O1 the smallest RMSmisfit correspond to TPXO7.2 (0.025m). The highest Root Sum Square (RSS) obtained from the RMSmisfits of the 8 constituents is obtained by CATS2008 (0.189m), while the rest of the models have a similar performance (lower than 0.088m). To analyze the individual performance of the models in 47 selected points, the RSS is calculated for each one. The analysis of the results shows that the errors are greater in the south of the latitude -63º and in the proximity of the 3 coastal tide gauges.

Ocean Response to Storms in the Bay of Biscay: Sensitivity to Atmospheric Forcing and Impact of Altimetric Data Assimilation

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We study the response of the ocean surface layers to extra-tropical winter storms in the Bay of Biscay using modeling experiments over the years 2008-2009. Our objectives are 1/ to characterize the impacts of a strong winds event on surface currents, surface temperature and mixed-layer depth, 2/ to better understand the sensitivity of the ocean response to uncertainties in the atmospheric forcing and 3/ to estimate the constraint brought by altimetric and high-resolution SST data if assimilated (through analysis of representers as well as data assimilation experiments). We mainly focus on the storm of March 10-11 2008. We use a stochastic modelling approach where an ensemble of simulations is generated by perturbing the wind forcing and infer the sensitivity from the ensemble statistics. Different regimes in the shelf and deep ocean are found, with large sensitivities of the sea surface temperature to wind forcing on the shelf. Large sensitivity are found on the temperature field at depths as large as 800-1000 m. Synthetic altimetric and SST observations are assimilated within OSSE experiments using an Ensemble Kalman filter. In particular, we aim at characterizing the impact of the assimilation during the storm on the temperature, surface currents and sea level fields. We also analyze the ocean response to storm Klaus (23-24 January 2009) in a free simulation, and assess the realism of the surface fields by comparing to available observations. Our study is based on the coastal regional model Symphonie, developed at POC/Laboratoire d'Aérologie (Toulouse, France), in a realistic configuration including tides, daily river runoffs and atmospheric pressure forcing.

Monitoring Sea Level by Tide Gauges and GPS at Estartit and Barcelona Sites for Altimeter Calibration Campaigns

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The tide gauge of l'Estartit is a traditional floating gauge placed 21 years ago and has an accuracy of ± 2 mm. Since 1996, l'Estartit tide gauge has been co-located with geodetic techniques (GPS measurements of XU, Utilitary Network, and XdA, Levelling Network,) and it is tied to the SPGIC (Integrated Geodetic Positioning System of Catalonia) project of the Cartographic Institute of Catalunya (ICC). In June 2008, new GPS and levelling measures have been done in order to tie the tide gauge new location into SPGIC project and to co-locate old data respect the new one. In the past three calibration campaigns for Topex/Poseidon and Jason-1 in March 1999, August 2000 and July 2002 near Cape of Begur.. A calibration campaign for Jason-1 was made in June 2003 in the Ibiza area. At Barcelona harbour there is one MIROS radar tide gauge belonging to Puertos del Estado (Spanish Harbours). It is placed at the dock 140 of the ENAGAS Building.The radar sensor is over the water surface, on a L-shaped structure which elevates it a few meters above the quay shelf. 1-min data are transmitted to the ENAGAS Control Center by cable and then sent each 1 min to Puertos del Estado by e-mail.This sensor also measures agitation and sends wave parameters each 20 min. A provisional tide gauge bench mark has been defined while the levelling has being done. There is a GPS station Leica Geosystems GRX1200 GG Pro and antenna 1202. Bathymetric campaigns inside the harbour have been made. The presentation is directed to the description of the actual situation of the geodetic infrastructure of Barcelona and l'Estartit sites for sea level determination and complementing Ibiza site for a new altimeter calibration campaign of Jason-2 and Saral/AltiKa satellites to be made in 2013.

Flood Wave Propagation Model of the Caspian Sea Based on Satellite Altimetry Data

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In this research simple flood wave propagation model was based the Saint-Venant equations represented a good way to describe problems concerning with flood waves propagations in open channels. For solution of this task the Caspian Sea was approximated as channel with a rectangular section. Channel axis coincided with the sea longitudinal axis or location of descending pass 092 of satellites TOPEX/Poseidon and Jason-1/2. Altimetric measurements of this satellites permit to define more exactly empiric parameters of the flood wave (propagation speed amplitude et al.) which are solution of the model. Also it allows estimating of effective evaporation. In this approach it is possible to consider as an integrated difference between sea surface heights between previous and the subsequent cycles altimetric measurements.

Results of calculations have confirmed well conformity given calculated by other researchers and the model. As is shown than interannual variability of flood wave speed in the North Caspian was well correlated with interannual the Caspian Sea level variability. However for the Middle and Southern Caspian Sea interannual variability of flood wave speed become in an antiphase to interannual sea level change.

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Satellite Altimeter view of Tropical Cyclone "Thane"

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Satellite observations of extreme weather events like Tropical Cyclones (TC) serve as essential inputs to scientific studies as well as for disaster management since they provide synoptic coverage of such events with good spatial and temporal resolution. This is essential for cyclone track prediction, determination of land fall points and estimation of areas of influence. Cyclone Thane, one of the TCs that developed recently in the Bay of Bengal (BoB) region of the north Indian Ocean, made a landfall along the coast of Tamil Nadu (India) on 30th December, 2011. The depression which developed on 25th December in the southern BoB, moved north and turned west around 12º N before reaching the coast. In the present work, high resolution satellite altimeter data from JASON-2 are used to observe the ocean and atmospheric parameters such as sea surface height anomaly (SSHA), wind and wave in the BoB along the altimeter track passing over TC Thane. JASON-2 (track no 116), passing through cyclone Thane on 27th December 2011 around 85.56º E, recorded a very high SSHA as well as considerably large change in slopes as compared to values during the pre and post cyclone recordings of the altimeter passes. The above observations have been verified with drifting buoy 23926 along the cyclone track, which recorded a pressure drop of as much as 993 mb. The work explores the scope of high resolution altimetry in the study of extreme events like cyclone Thane.

Ocean Tide Modeling from Satellite Altimetry: the Challenge in the Arctic Ocean

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The global ocean tide model DTU10 (Technical University of Denmark) representing all major diurnal and semidiurnal tidal constituents has been proposed based on FES2004 and the response method (Cheng and Andersen, 2011). In the model, four years of TOPEX-Jason-1 primary interleaved mission time series were used for sea level residual response analysis.

The model is revised and upgraded using several additional datasets and method improvements. One is the introduction of six years of TOPEX-Jason-1 primary interleaved mission into 20 years (1993-2012) of primary joint TOPEX, Jason-1, and Jason-2 mission time series. In the upgraded model, a new combined "reprocessed" Envisat- GEOSAT Follow-On as well as ERS-1 and ERS-2 data sets have been included to solve for the tides up to the ±82º parallel. Particularly in the Arctic the revised processing of the ENVISAT and ERS data recovers up to 3 times as many data as before. The main obstacle in the Arctic is the fact that the diurnal constituents K_1 and $P_1$from the sun-synchronous satellite (e.g., ERS-2 and Envisat) have alias periods of exactly 1 year (365 d), which makes them inseparable from the annual signal and each other. To decrease the effects of annual signal on the diurnal constituent estimation, a new global model for the annual sea level variation (DTU10ANN) is used to removing the annual sea level variations prior to estimating the residual tides of diurnal constituents from the Sun-synchronous satellites in the Arctic Ocean, where the magnitude of the annual signal is comparable to the residual ocean tide signal.

Comparison with the FES2004 reference model and other state-of-the-art global ocean tide models, the harmonic constituents of four principle constitutes (M_2, S_2, K_1, O_1) from the new tide model solutions fit tide gauge measurements better both in deep ocean and coastal regions, especially in the Arctic Ocean.

The Annual Signal in the Arctic Ocean: Implications for Ocean Tides and Mean Sea Surface Determination

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In the Arctic Ocean, sea level has a significant annual cycle along the coastal zones, for example, the magnitude of the sea level annual signal is larger than 10 cm along the Russian coastline. It is of fundamental importance to include knowledge about the annual signal for both tidal and the sea level trend studies.

For tidal studies, the problem is mainly, that the diurnal constituents K_1 and P_1 from the sun-synchronous satellite (e.g., ERS-2 and Envisat) have alias periods of exactly 1 year (365 d), which makes them inseparable from the annual signal and each other.

For studies of sea level trend the altimetric observations are taken as different locations throughout the year as a consequence of the variation in sea-ice distribution.

In order to perform a robust estimation of linear sea level trend the annual signal must be modeled as well to account for the spatial variations of altimetry observations.

To solve for the annual signal in the Arctic Ocean, the DTU10ANN model of global annual sea surface anomalies has been calculated from the global model GECCO using data from 1992-2004, which is a part of ECCO (Estimating the Circulation and Climate of the Ocean, National Ocean Partnership Program). In a test of 4 sea surface height models, GECCO proved to be the best compared to altimetry data from TOPEX/Jason, ERS-2/Envisat and ICESat in the period from 1995-2010. In many regions the amplitude and phase signals returned from the model data had to be adjusted to the altimetry data to obtain DTU10ANN.

This model is then applied to the satellite altimetry from combined ERS-2, Geosat Follow-On (GFO) and Envisat for the subsequent studies of ocean tides in the Arctic region. The removal of annual signal in the sea level residuals in the combined Envisat, GFO, and ERS-2 satellite altimeter data prior to tidal prediction significantly lowers the contribution of nontidal variability at the aliased tidal frequencies and improves the determination of the ocean tide constituents. The application of the model to the satellite altimetry from ERS-2 and ENVISAT for improves the determination of mean sea surface in the Arctic Ocean.

Shallow water Tides on the Patagonian Shelf and Yellow Sea

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The tidal analysis of multi-mission altimeter data has been proven as powerful tool for the empirical tide modeling in shallow water. Even such small tides as 2SM2 or 2MS6 could be detected on the Northwest European Shelf. The Patagonian Shelf and Yellow sea are other areas with exceptional tidal regimes what make them to the challenge for hydrodynamic modelling. As example the residual amplitudes w.r.t. FES2004 tide model exceed the decimeter level for astronomic tides. Besides of exceptional powerful astronomic tides the non-linear tides become significant and have to be considered in order to achieve accurate description of tidal regimes. As analysis method the residual harmonic analysis is chosen because of the danger that the admittance functions were affected by the tidal resonance and non-linear tides overlapping with the spectra of astronomic tides. To prove separation between estimated tides the correlation analysis has to be carried out. The internal accuracy of the results is checked by means of the statistics of crossover differences. To obtain the absolute quality measure the external data like bottom pressure and coastal tide gauges are used.

Improved Coastal Ocean Tide Modeling Using Satellite Altimetry

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Ocean tides, resulting from the gravitational attractions of the Moon and the Sun, represent 80% of the ocean surface topography variability, is of practical importance for commerce and science over thousands of years. Tides also have strong influence on modeling of coastal or continental shelf circulations, play a significant role in climate due to its complex interactions between ocean, atmosphere, and sea ice, dissipate their energy in the ocean and solid Earth, and decelerate the Moon's mean motion. Oceanography studies and applications, including coastal or continental shelf ocean circulations, require their observations to be 'de-tided' using ocean tidal forward prediction models for better geophysical or oceanographic interpretation, particularly over coastal regions. Advances in satellite radar altimetry technology enable a globally sampling observational record of accurate sea surface topography and its changes over 2 decades for numerous scientific studies, including the accurate determination of ocean tide models with improved predictability. Perhaps an unexpected but significant contribution to global ocean tide modeling is owed to the advent of TOPEX/POSEIDON satellite altimetry. Numerous contemporary ocean tide models have been determined either through the assimilation of satellite altimetry and coastal tide gauge data, the 'assimilation models' (e.g. FES2004, NAO.99b and TPXO7.2), or via the direct use of altimetry observations in an 'empirical modeling' approach adjusting tidal constituents based on a-priori assimilation models (e.g. EOT11a, GOT4.7). However, ocean tide model accuracy is still much worse in the coastal regions and partially or permanently sea-ice covered polar ocean, or over the ice-shelves. Here we report the advances in empirical barotropic ocean tide modeling, with a focus in the world's coastal regions and over continental shelf areas, using multi-mission satellite radar altimetry data, including data from TOPEX, Jason-1/-2, Envisat, GFO, and other data (possibly ERS, CryoSat-2), in a spatio-temporal variance component adjustment approach to combine the different data, to mitigate tidal aliasing and to improve error modeling. Our intent is also to improve spatial resolutions of the empirical tide model especially near coastal regions where radar altimetry data are degraded by land surface or energetic coastal ocean dynamics. Evaluations of the resulting ocean tide model via comparisons with other contemporary models in variance reduction studies using independent data sets, including pelagic tidal constant from tide gauges and altimetry sea-level data, indicate an improvement in the tide model in terms of accuracy and increased spatial resolution.

Unexpected Contributions of Satellite Radar Altimetry to Tsunami Research

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Satellite altimeters were not initially designed for observing tsunamis because tsunamis were not believed to happen often enough, and it is not always feasible to observe a fast propagating wave from space. Surprisingly, satellite altimeters had observed all the recent mega tsunamis, revealed previously unknown features and revised long-hypothesized theories. For the first time, satellite altimeters unambiguously observed tsunami waves in the open ocean after the 2004 Indonesian earthquake. The observations were close to the epicenter, leading to new development of the tsunami genesis theory [Song et al, 2005; 2008]. In 2010, satellite altimeters observed the Chilean tsunami in the Southern ocean, providing successful testing of using ground GPS networks for early detection and warnings [Song 2007]. Most recently, three satellites observed the 2011 Tohoku-Oki earthquake-induced tsunami, and for the first time, one of them, at the right time and location, recorded a tsunami height about twice as high as that of the other two, confirming the long-hypothesized tsunami merging theory that can double its destructive potential in certain directions [Song et al 2012]. These altimetry observations have advanced the understanding of tsunami dynamics as well as provided test of a new approach to tsunami early detection and warnings. This talk will review these unexpected, but significant and unique contributions from satellite altimetry to tsunami research, their potentials for hazard mitigation, and an outlook for the use of the future swath interferometric altimetry, i.e., NASA's/CNES' Surface Water and Ocean Topography, for improved tsunami observations and research.

Poster Session: Outreach

Altimetry Products and their Users: Feedback from Aviso

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For 20 years, Aviso has been Cnes altimetry mission user services. Set up in 1992 for Topex/Poseidon, the data dissemination and information services continue on. Aviso user service's activities now encompass:

- ☐ operational distribution of Topex/Poseidon, Jason-1 and Jason-2 GDRs;
- ☐ operational distribution of multimission Ssalto/Duacs Near-real and delayed time products;
- ☐ distribution of high-level altimetry products;
- ☐ a catalog of altimetry, orbit determination and precise location products;
- ☐ promotion of ocean altimetry, orbit determination and precise location activities.

Along those years, Aviso had to evolve alongside with the users. From the altimetry experts of the first years to the PhD students working in non-physical oceanography, or to the end-users wanting to use those data for practical applications, focii have considerably broadened. At the same time, technology also changed, with online and interactive data dissemination becoming commonplace.

Challenges in the next years will be interactive user-defined data distribution, easiness of use of the data. Aviso user services is building on its experience to try and face them, working hard to foster closer and closer collaboration between project teams and data users.

Basic Radar Altimetry Toolbox: tools to use altimetry

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The Basic Radar Altimetry Toolbox is an "all-altimeter" collection of tools, tutorials and documents designed to facilitate the use of radar altimetry data, including the next mission to be launched, Saral. It has been available from April 2007, and had been demonstrated during training courses and scientific meetings. Nearly 2000 people downloaded it (January 2012), with many "newcomers" to altimetry among them. Users' feedbacks, developments in altimetry, and practice, showed that new interesting features could be added. Some have been added and/or improved in version 2 to 4. Others are under development, some are in discussion for the future.

The Basic Radar Altimetry Toolbox is able:

- ☐ to read most distributed radar altimetry data, including the one from future missions like Saral, Jason-3
- ☐ to perform some processing, data editing and statistic,
- ☐ and to visualize the results.

It can be used at several levels/several ways, including as an educational tool, with the graphical user interface. As part of the Toolbox, a Radar Altimetry Tutorial gives general information about altimetry, the technique involved and its applications, as well as an overview of past, present and future missions, including information on how to access data and additional software and documentation. It also presents a series of data use cases, covering all uses of altimetry over ocean, cryosphere and land, showing the basic methods for some of the most frequent manners of using altimetry data.

Example of uses will be presented, and feedback from those who used it will be most welcome.

BRAT is developed under contract with ESA and CNES. It is available at http://www.altimetry.info and http://earth.esa.int/brat/

GOCE User Toolbox and Tutorial

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The GOCE User Toolbox GUT is a compilation of tools for the utilisation and analysis of GOCE Level 2 products. GUT support applications in Geodesy, Oceanography and Solid Earth Physics. The GUT Tutorial provides information and guidance in how to use the toolbox for a variety of applications. GUT consists of a series of advanced computer routines that carry out the required computations. It may be used on Windows PCs, UNIX/Linux Workstations, and Mac. The toolbox is supported by The GUT Algorithm Description and User Guide and The GUT Install Guide. A set of a-priori data and models are made available as well.

Recently, the second version of the GOCE User Toolbox (GUT) was developed to enhance the exploitation of GOCE level 2 data with ERSENVISAT altimetry. The developments of GUT focused on the following issues: Data Extraction, Generation, Filtering, and Data Save and Restore Without any doubt the development of the GOCE user toolbox have played a major role in paving the way to successful use of the GOCE data for oceanography. The results of the preliminary analysis carried out in this phase of the GUTS project have already demonstrated a significant advance in the ability to determine the ocean's general circulation. The improved gravity models provided by the GOCE mission have enhanced the resolution and sharpened the boundaries of those features compared with earlier satellite only solutions. Calculation of the geostrophic surface currents from the MDT reveals improvements for all of the ocean's major current systems.

CTOH: 20 Years of Altimeter Data

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The Center for Topography of the Oceans and Hydrosphere (CTOH) is a French Observation Service created in 1989 and dedicated to satellite altimetry studies. Its objectives are to 1) maintain and distribute homogeneous altimetric databases for ocean, hydrosphere and cryosphere applications, 2) help scientific users develop new altimetry derived products and 3) contribute to the development and validation of new processing approaches of the altimetric data for emerging research domains.

The CTOH maintains homogeneous altimetric GDR data bases for the following missions : Topex/Poseidon (1992 - 2005); GFO (2000 - 2008); ENVISAT (2002 - today); Jason-1 (2002 - today); Jason-2 (2008 - today) covering the 20 years of altimetry data.

Both 1Hz and 18-20Hz data are available over all possible oceanic and continental surfaces. In addition we add about 20 recent corrections in a homogeneous way to all of the missions. These include tide models, DAC, MSS, geoids, and tropospheric corrections. Retracking of ERS-1 and ERS-2 waveform with the ICE-2 algorithm is underway.

A web-based tool allows users to select,visualize and download data using spatio-temporal criteria (http://ctoh.legos.obs-mip.fr/). This tool is complementary to the AVISO website, and BRAT Toolbox, as it allows users to extract GDR data and homogeneous corrections in regions where the standard products and data are not adapted: coastal zones, continental water surfaces and the cryosphere.

In addition, the CTOH works on developing and distributing new altimetric products which can be accessed from the web site (http://ctoh.legos.obs-mip.fr/products). These include :

Coastal products : Alongtrack data are available in a dozen regions, with specific X-TRACK processing in the coastal band. SLA are available on a nominal groundtrack (1hz and 20hz for some regions), as well as a high-resolution MSS (.../products/coastal-products).

Tidal constants (amplitude and phase lag with error estimations for each tidal constituent) have een newly added ton this product.

Continental hydrology products : including the "Hydroweb" data base for monitoring river and lake levels (.../products/hydroweb). Hydroweb now integrates the CASH project Topex reprocessed data over terrestrial surface waters.

Global Surface Current product, combining altimetric geostrophic anomalies, mean currents based on the MDT_CNES_CLS09_v1.1, and QuikScat Ekman currents up till 2009, and under extension using EKMAN (.../products/global-surface-currents).

Global SubMesoscale filaments. Amplitude and position of sub-mesoscale filament barriers calculated from gridded AVISO surface currents using the Finite-Size Lyapunov Elements (d'Ovidio et al., 2009), at 4 km resolution from 1993 to today (.../products/submesoscale-filaments).

Regional Maps of Sea Level Anomalies: The maps are derived from 1Hz multi-satellite coastal altimetry (X-TRACK) data. This promizing product is under evaluation (Dussurget et al., 2011).

SPACYBA, a Website dedicated to distributing Satellite Data and processing Tools for Hydrology

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The SPACYBA website is a new website dedicated to an open distribution of spaceborne products and modelling tools of interest for the large hydrological basins. The goal of this website is to be a meeting point between the various communities of hydrology-related expertise, with the specific hope that more hydrologists become familiar with the spaceborne data.

As a start, the data type that the website distributes are time series of water levels obtained by the processing of radar altimetry missions. Currently, time series in the Amazon, Congo and Orinoco basin are available. Other tropical basins shoudl come soon. Other datatype are foreseen. They include altimetry-derived climatologies of river stage and associated discharges, inundated surfaces, DEMs, drainage networks, rainfall rates, and so on...

As far as tools are concerned, two tools are curruntly being implemented. First one is dedicated to the guided processing of altimetry GDRs for the computation of water level time series and the second one is for the determination of discharge/height rating curves with a Mushkingum-Cunge scheme tuned for altimetry series.

This website is collaborative. That means that it will not reflect the work of a specific lab, but distribute the products, results, models and documentation provided by any people who wish to participate to the website. As an example, the altimetry series already distributed by the SPACYBA website come from University of Manaus, Brazil, University of Palmira, Colombia, and LEGOS and Espace IRD teams in France. As a consequence, this website is not aimed to be global but to be as rich as possible on a few basins.

SENTINEL-3 Payload Data Ground Segment (PDGS) Overview

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The Sentinel-3 Payload Data Ground Segment (PDGS) will be in charge of executing the acquisition, processing, archiving and dissemination of data from the OLCI (Ocean and Land Colour instrument), the SLSTR (Sea and Land Surface Temperature Radiometer) the SRAL (Synthetic Aperture Radar Altimeter), the MWR (Microwave Radiometer) instruments, and the GNSS and DORIS assembly embarked in the Sentinel-3 satellite.

The Sentinel-3 PDGS will be consisting of centres with the following functionalities: Core Ground Station(s) providing acquisition and Near-Real-Time LAND Processing functionality;

Land PDGS Centre(s) providing Offline Processing, Auxiliary Data Coordination, Mission Performance Monitoring, User Interface and Long Term archiving functionality for LAND products.

fnMarine PDGS Centre providing Processing, Mission Planning, Mission Performance Monitoring, User Interface and Long Term archiving functionality for MARINE products;

Circulation, Short Term Archiving, Online Archiving and Monitoring functionality are common to all Centres.

This poster provides an overview of the Sentinel-3 PDGS, with its different centres and functionalities, including data and products which will be generated operationally by the Sentinel-3 PDGS.

Access to ESA Radar Altimetry Data

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ESA/ESRIN, the European Space Agency Centre for Earth Observation (EO), is a large European EO data provider which operates a distributed ground segment for EO payload data exploitation. ESA distributes data from ESA EO Missions, ESA Campaigns, the GMES Space Component (GSC), and Third Party Missions (TPMs) from many European and non-European EO data providers. This paper provides an overview of the practical procedures required for access to ESA Radar Altimetry data, in particular for ERS, Envisat and CryoSat missions. Various types of altimetry data provided by ESA and available access mechanisms for the required data will be described, including the on-line registration process via ESA's Earthnet Online portal and the use of EOLi (Earth Observation Link), ESA's client for EO multi-mission data catalogue and ordering services. A summary of the terms & conditions for the utilisation of ESA EO data will be presented. Furthermore, future enhancements to the ESA on-line data access will be outlined to inform the EO user community of the potential improvements.

Progress in OSTM/Jason-2 Science Application Study and Data Discovery/Access Tools Development at NOAA National Oceanographic Data Center (NODC)

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Compared to NOAA's other satellites, the Jason-2 altimeter is uniquely designed to observe the sea surface height anomaly and significant wave height on the ocean surface. It can be applied in real-time monitoring of changes of the sea surface across tsunami waves and the wave activities around a hurricane. Using Environmental Systems Research Institute's (ESRI's) Geographic Information System (ArcGIS) software, we have developed high-quality georeferenced visualizations of Jason-2 data. In one product, we overlaid the sea surface height anomaly from the Jason-2 observed final Geophysical Data Records (GDR) onto the Tsunami Travel Time (TTT) maps produced by NOAA's National Geophysical Data Center (NGDC); a sharp rise in sea level in the southwestern Pacific Ocean at 02:03 PM on 11 March 2011 is associated with the arrival of the tsunami wave produced by the Honshu, Japan earthquake 8 hours and 17 minutes previously. We also investigated the wave height variations from the operational GDR (OGDR) associated with Hurricane Irene while it progressed along the U.S. Atlantic coastline from 21-28 August 2011. These applications explored the possibility of applying near real-time Jason-2 satellite data to earth system monitoring, especially for those natural disasters having an effect on the ocean surface.

In its role as the U.S. archive for oceanographic data, the NODC provides near real-time distribution and long-term data stewardship for Ocean Surface Topography Mission (OSTM)/Jason-2 data and products. Since the last OSTST meeting, remarkable progress was made at NODC in the data quality monitoring system (data Rich Inventory), in the establishment of RSS feed homepages, in the improvement of the data discovery through a Geoportal server for both collection-level and granule-level data, and great reduction in the latency (delay) in public access to Jason-2 Geophysical Data Records (GDRs).

Multimedia Contents, Interactive Features and Social Network Tools all in One. How Far this Synergy can Improve Learning of Complex Topics as Altimetry?

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Multimedia contents have longer demonstrated their great value in improving training and communication effectiveness, whereas there isn't yet a clear idea on the effect on knowledge and learning process of educational tools based, all together, on multimedia, interactivity and social network.

The poster will describe a research undertaken by Gruppo Dida, L'Aquila University and the ESA education department regarding the effect of a digital manual on Geography, based on all of these elements, to be targeted to secondary European schools (students between 13 to 18 years) and will describe how its results could become useful in the teaching of any complex topic as altimetry is. The manual to be realized at the end of this study will take care also of the most common learning disorders as word blindness and deafness with an accurate use of multimedia technologies. For example it will provide, on request, subtitles for each audio content and an audio support for each text (always on demand - by selecting a button).

At the basement of our research there is also another important factor: the impact of sense involvement in educational process. Many international researches have already stated how much an immersive and emotional environment can improve brief and long memory and facilitate information acquisition. This beneficial effect of emotional environment on learning grows up with a "digital native" target as young people. Starting from this assumption we want to verify if a multimedia manual, rich of beautiful images, video and animations, exercises and interactions and link to social network tools can really provide better learning results and in case in what percentage. Our initial hypothesis is that these kinds of contents could arrive to cause a real revolutionary effect also in the didactic methodologies at school, inverting current didactical processes: the study will be done at home on a digital content realized with all the best technology and methodologies while the exercise will take place in classrooms. We believe this inversion will allow the teacher to customize learning for each student providing just the needed support, allowing to remove any learning gap and obstacle. The research will tell us if this effect can really occur.

Status and Perspectives on Education and Outreach in Radar Altimetry

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Altimetry is becoming increasingly popular, now extending its audience to marine biologists, chemical oceanographers, climatologists, meteorologists, university students and even secondary education. The geographical distribution of users is also becoming more diverse, with more and more developing countries joining the altimetry (end)user community.

Space agencies like ESA and CNES, along with many partners worldwide, are particularly active in Education, Capacity Building and Outreach for Earth Observation. A variety of activities are being carried out, ranging from training courses, workshops and other events for schools, universities and professionals, to special publications, on-line material and software development.

In this article we provide an overview of the status of education and outreach activities in Remote Sensing from Space, where radar altimetry is included as a topic. We also describe the relevant toolboxes (BRAT, GUT) and the training opportunities for the next generation Principal Investigators and Scientists, in which ESA and/or CNES are involved. Finally, we conclude with the education and outreach challenges and ESA/CNES strategy for the next years, as well as the adoption of e-Education, always with emphasis on radar altimetry.